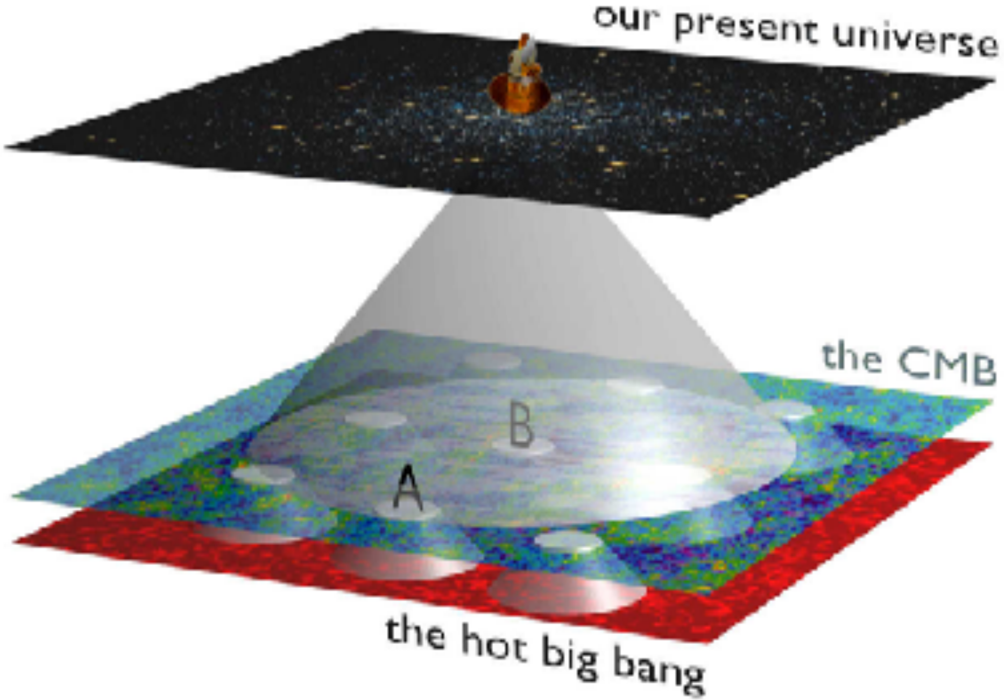
Gravitational waves and new physics

Anastasiia Filimonova, Sascha Leonhardt, Thomas Rink

Horizon problem

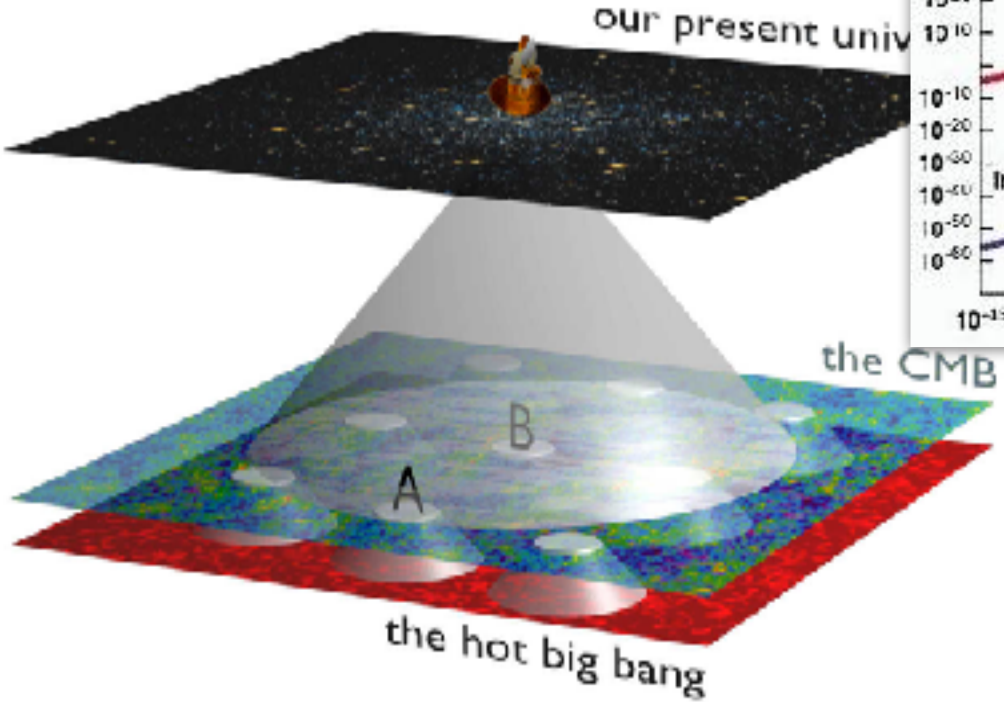
$$ds^2 = a(\tau)^2(-d\tau^2 + d\mathbf{x}^2)$$

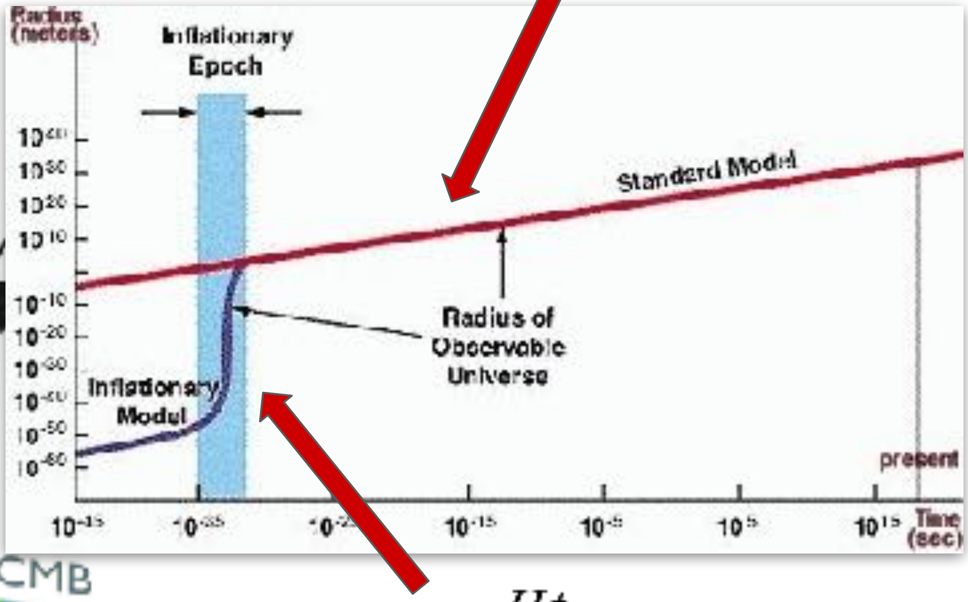


Horizon problem

$$ds^2 = a(\tau)^2(-d\tau^2 + d\mathbf{x}^2)$$

$$a \propto \sqrt{t}$$





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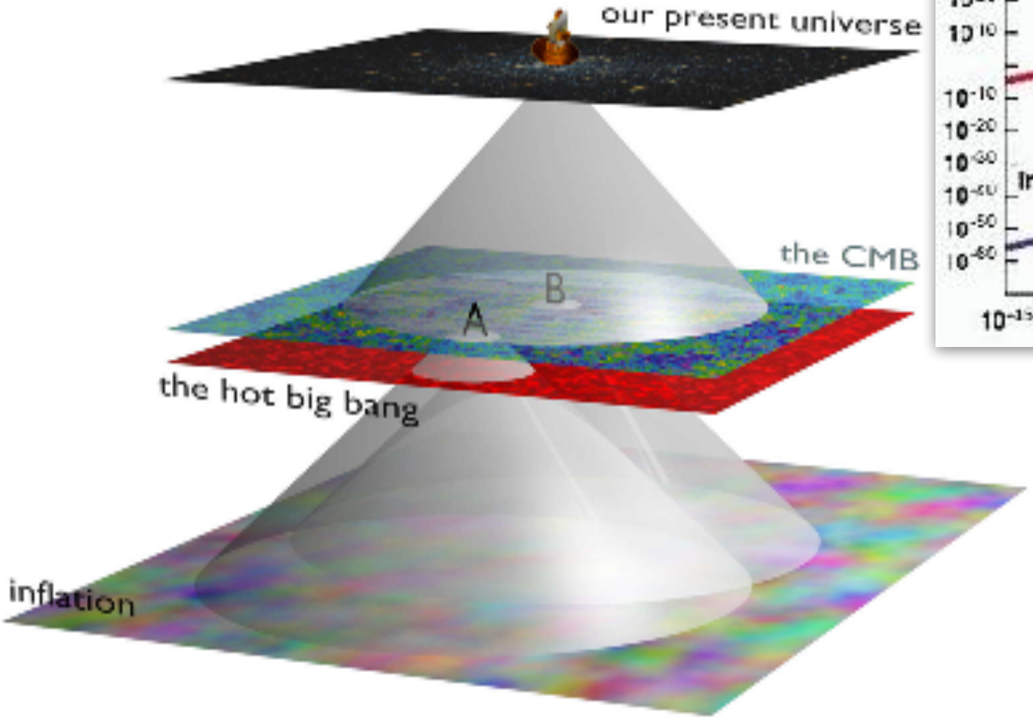

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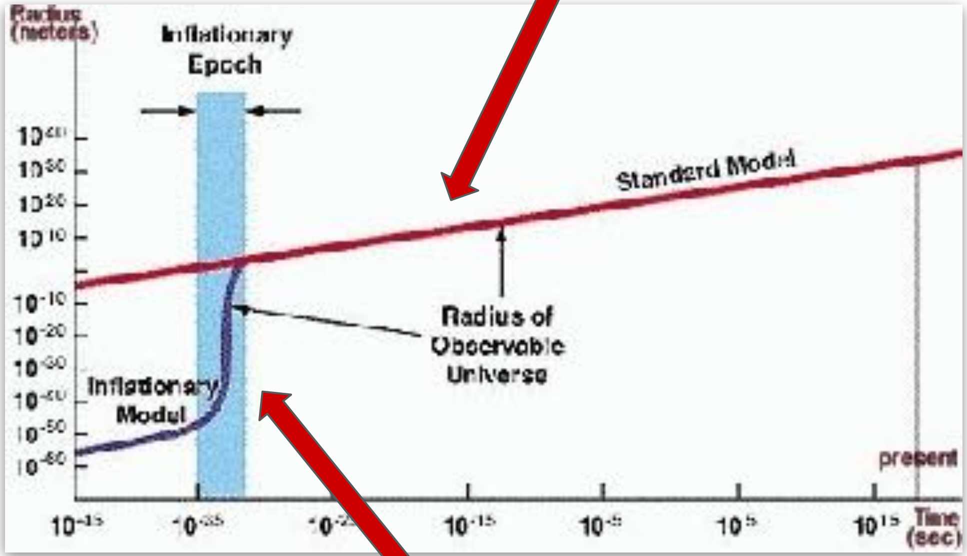

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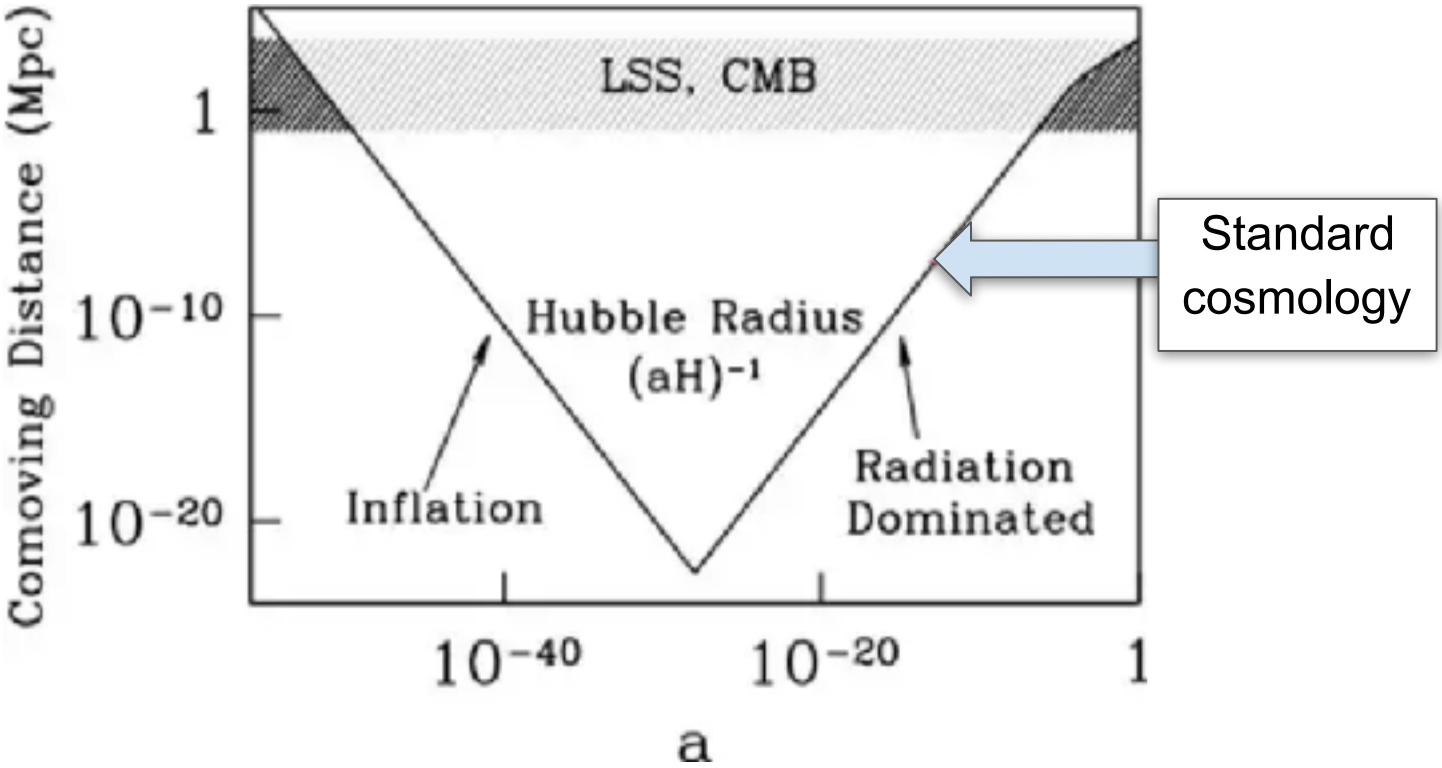
Evolution of the horizon



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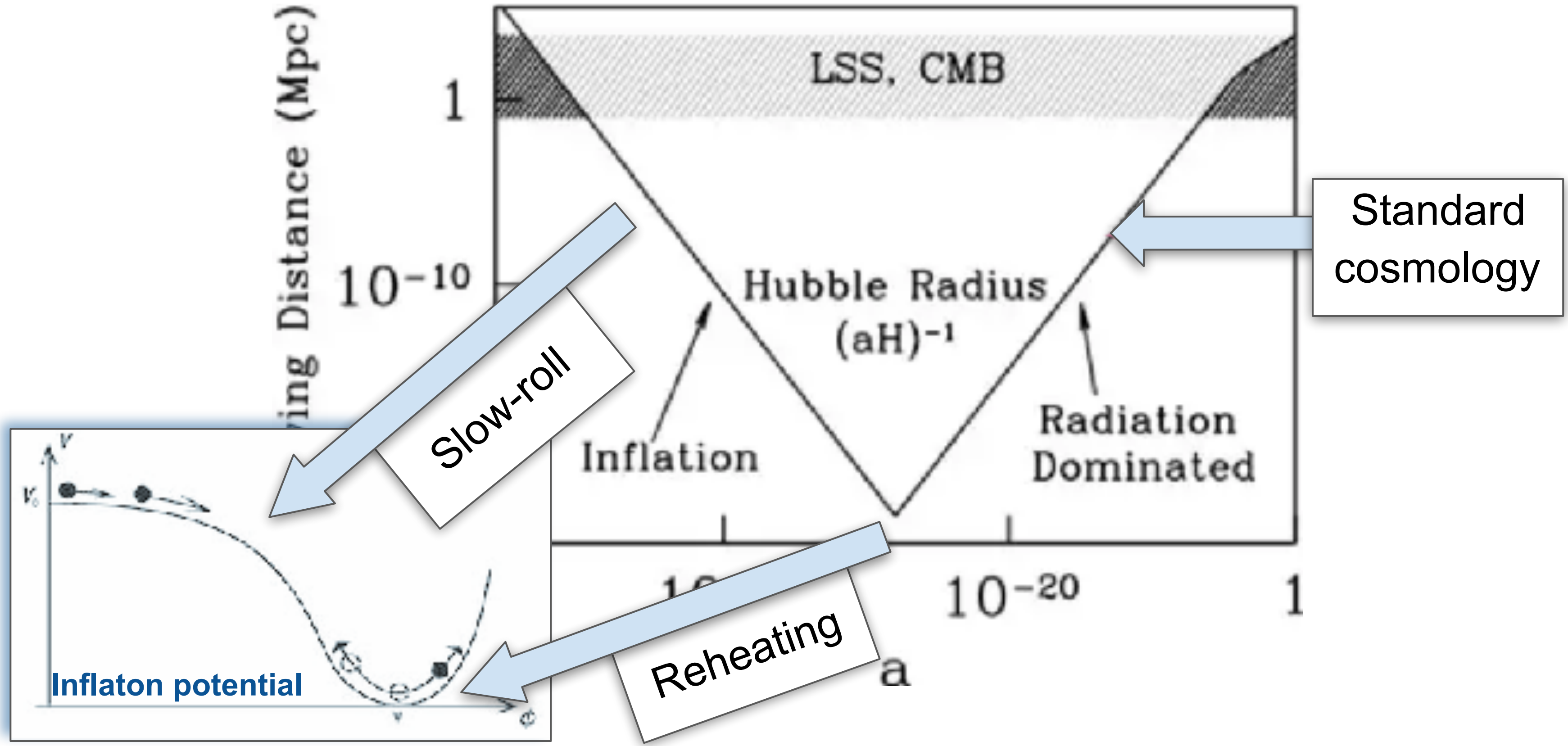
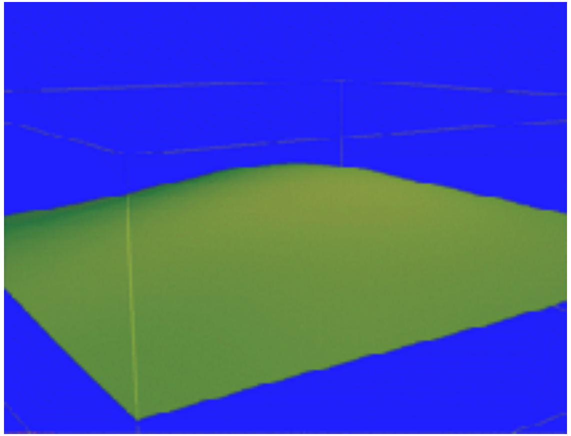


Quantum fluctuations

Quantum fluctuations



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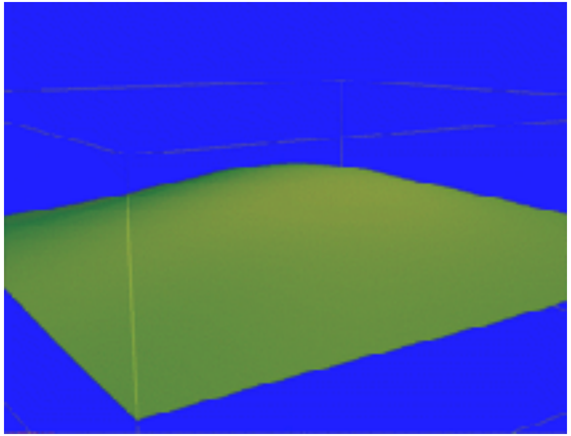

- **Scalar perturbations:** curvature perturbations induced by spatial fluctuation in scalar field.

Power spectrum: $\Delta_r^2(k) = \frac{k^3}{2\pi^2}\langle |R_k|^2 \rangle$

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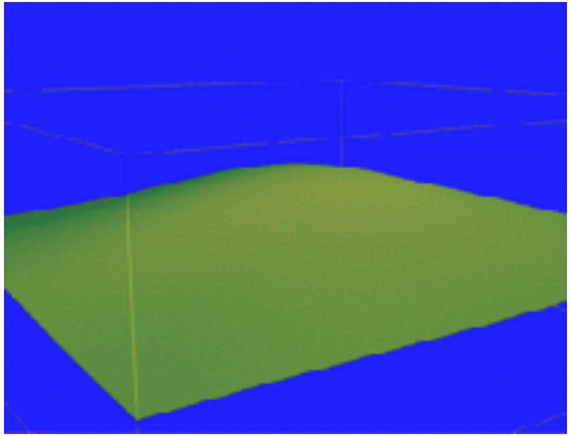

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Power spectrum: $\Delta_h^2(k) = 2\frac{k^3}{2\pi^2}\langle |h_{p,k}|^2 \rangle$

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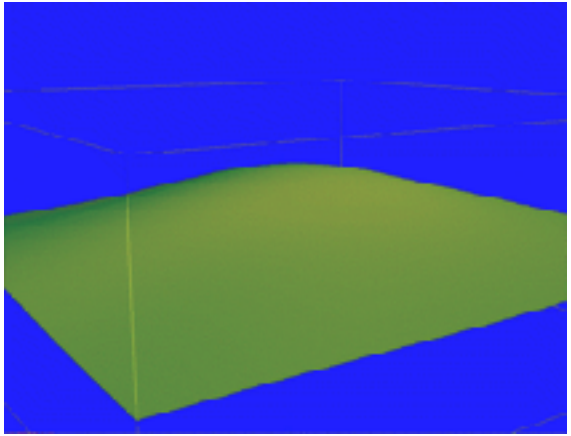

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Tensor-to-scalar ratio

(normalized amplitude)

$$r \equiv \frac{\Delta_h^2(k)}{\Delta_R^2(k)} \simeq \left(\frac{V}{[2\times 10^{16}\ \mathrm{GeV}]^4}\right)$$

($\Delta_R^2(k)$ is known from $\langle T^2(k)\rangle$, $H^2 \propto V$)

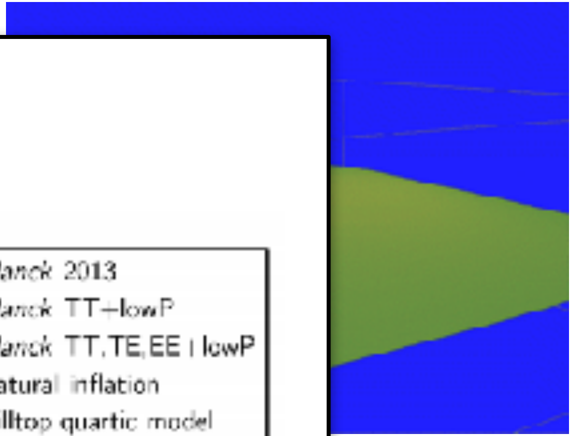
Quant

- **Scala**
by spa

Po

- **Tens**

Po



ratio
tude)

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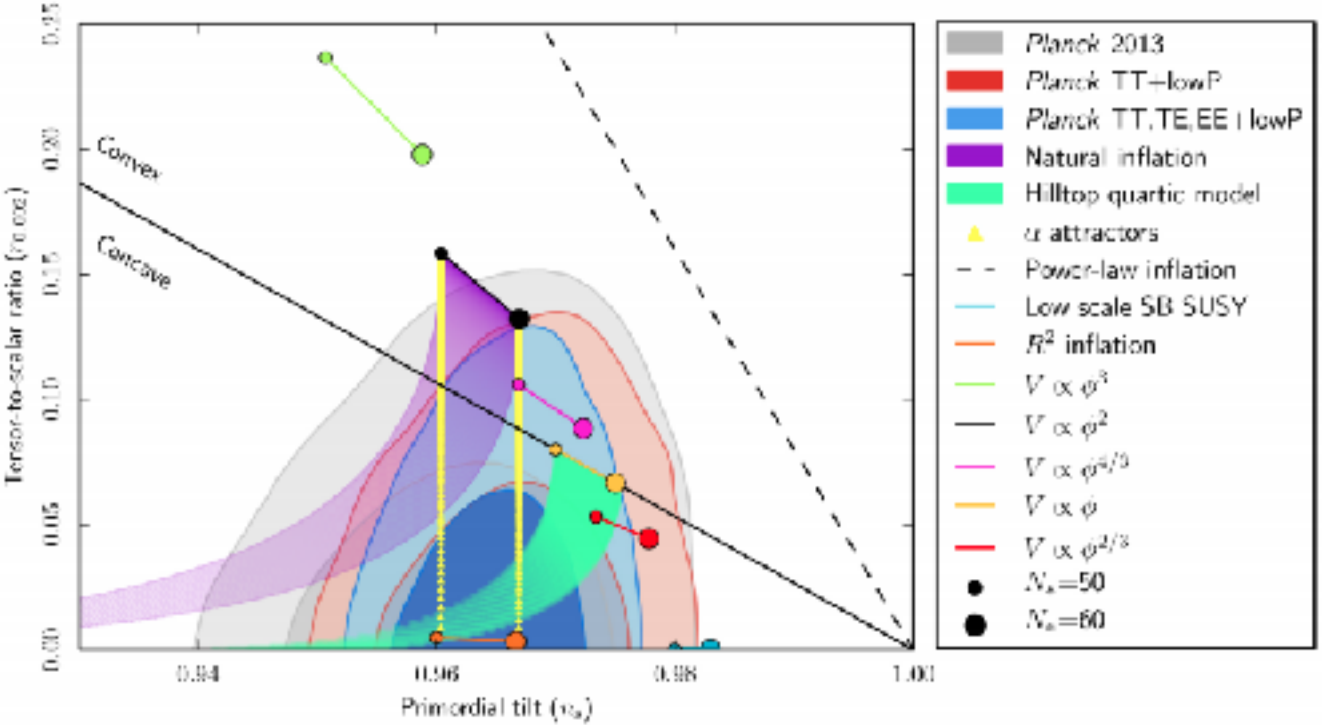
Test your favourite model!



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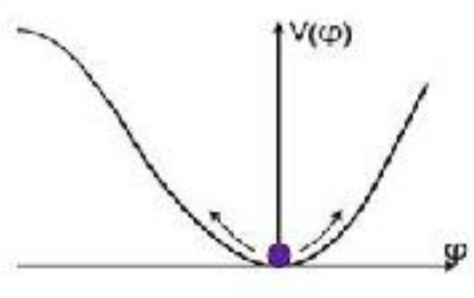

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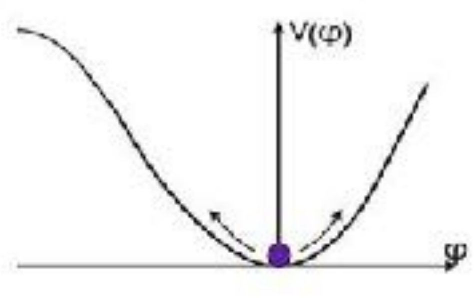

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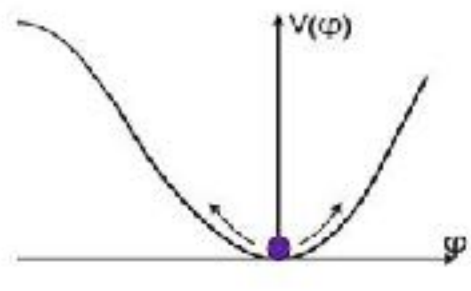

If large and coherent

Non-pertrubative processes

Time-dependent inhomogeneities in the energy-density.

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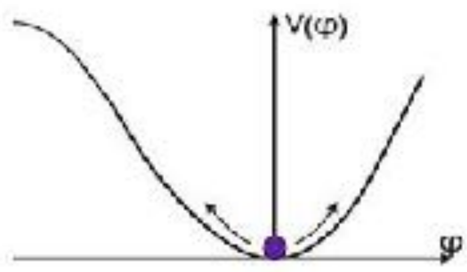

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Non-pertrubative processes

Time-dependent inhomogeneities in the energy-density.

Non-trivial quadrupole moments.

Why interesting?

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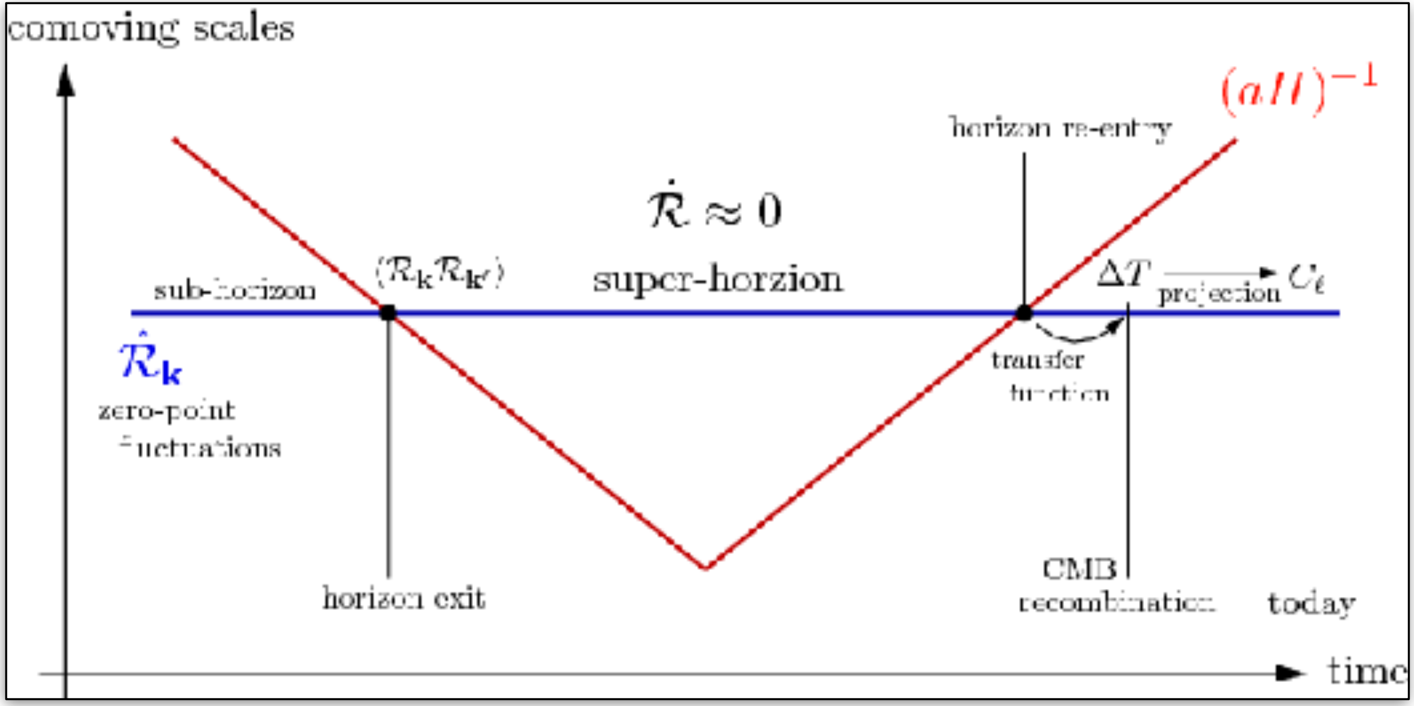

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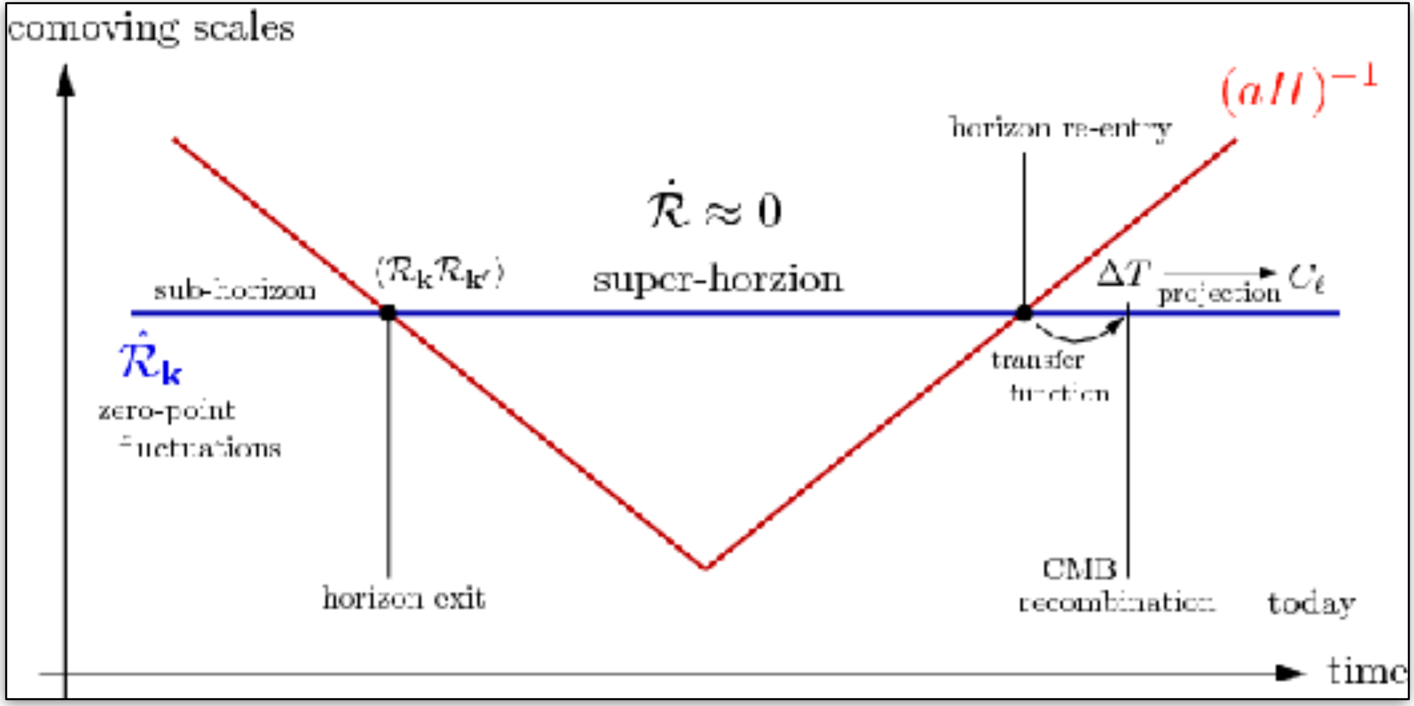
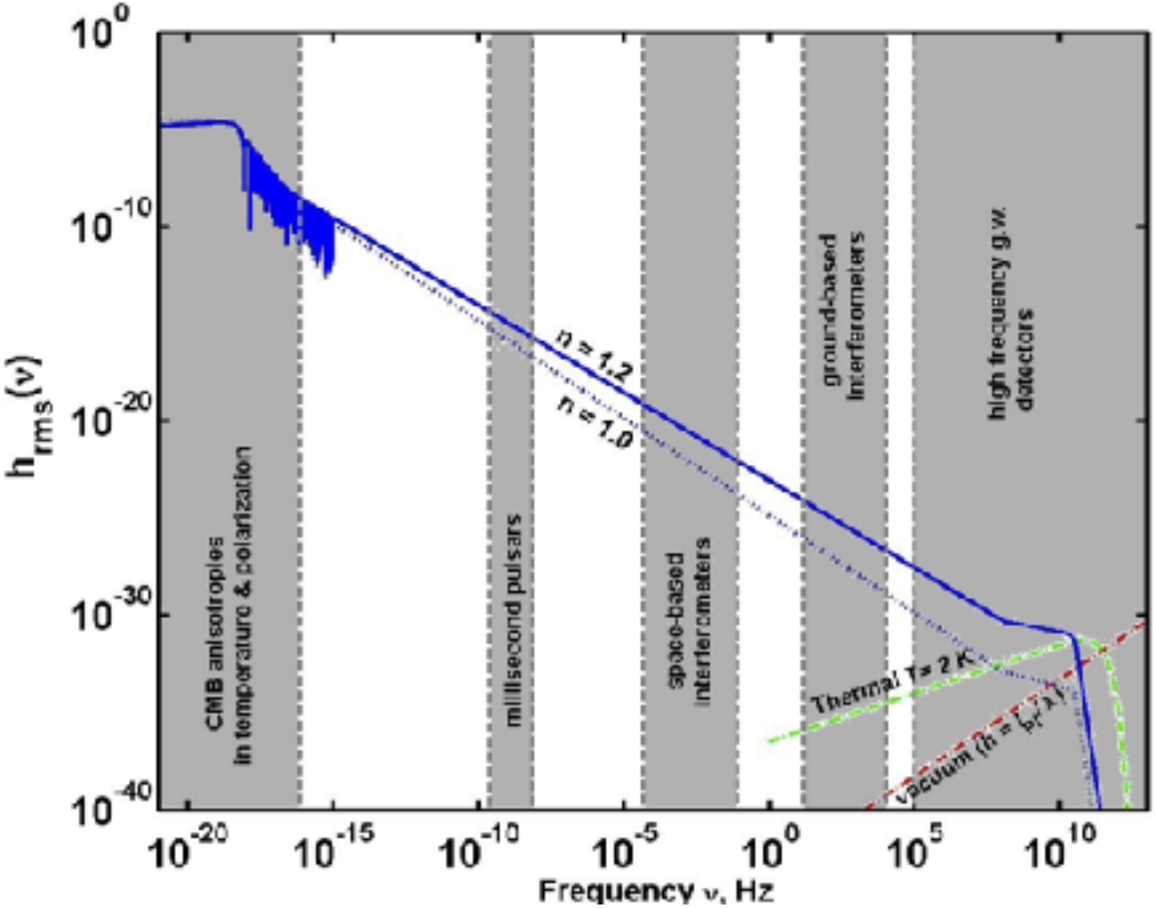


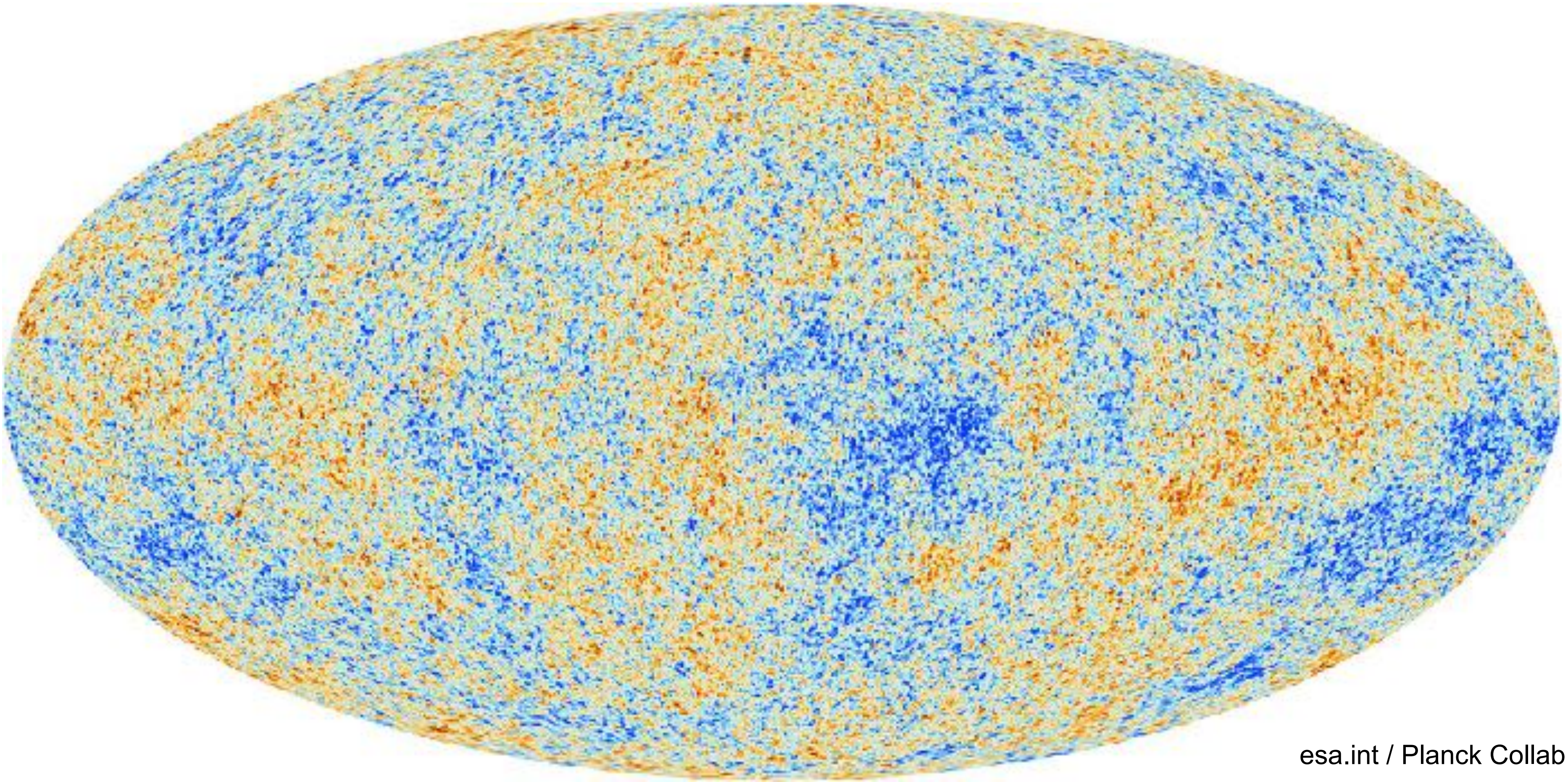
Model-independent evidence of inflation!

A small motivation for indirect detection



arXiv:0707.3319 [gr-qc]

The CMB - A Screenshot of Primordial Gravitational Waves



esa.int / Planck Collab

GWs  CMB

- primordial GWs **too faint to detect directly**
- GWs generate anisotropies in the matter distribution
- at the time of decoupling this results in anisotropies of CMB
- indistinguishable from (more dominant) scalar quantum fluctuations
- however: **B-mode** polarization of CMB is **unique to GWs**!
- power of B-polarized CMB waves (in inflationary low frequency band) gives tensor-to-scalar ratio r

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Detection of B-modes proves existence of primordial GWs!

What are E- and B-Modes?

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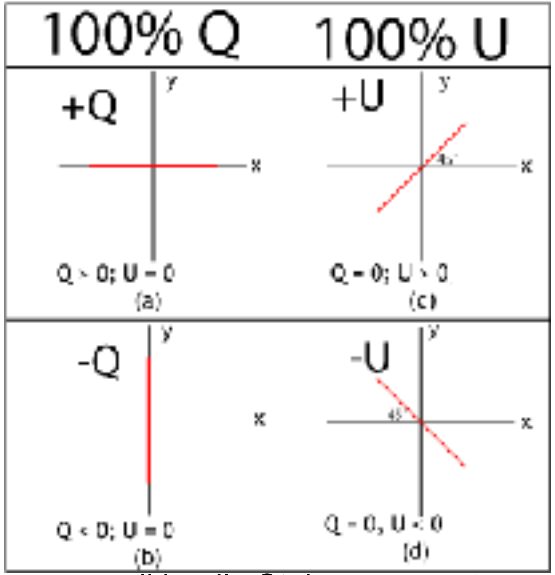
- Information in CMB: temperature $T(\hat{n})$ and polarization $Q(\hat{n})$ and $U(\hat{n})$ as function of position $\hat{n} = (\theta, \phi)$
- Polarization measured by symmetric, traceless tensor:

$$\mathcal{P}_{ab}(\hat{n}) = \begin{pmatrix} Q(\hat{n}) & U(\hat{n}) \\ U(\hat{n}) & -Q(\hat{n}) \end{pmatrix}$$



wikipedia:Stokes parameters

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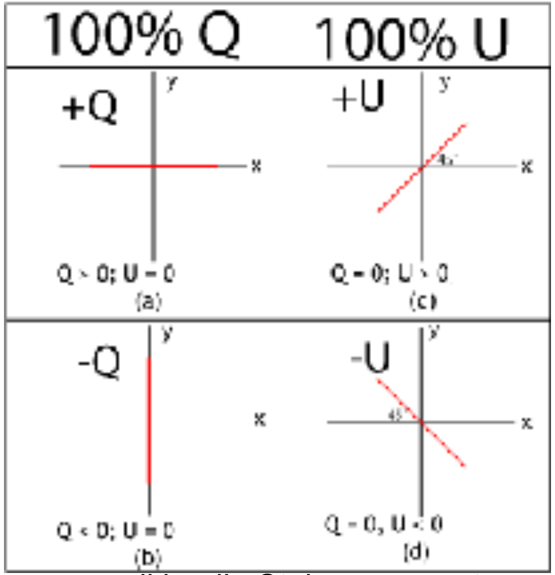
- Just like $V_a = \nabla_a E + \epsilon_{ab} \nabla_b B$ we decompose

$$\mathcal{P}_{ab} = \nabla_a \nabla_b E + \epsilon_{ac} \nabla_b \nabla_c B$$

(+ symmetrization - trace),

where $E(\hat{n})$ is “the **gradient**” and $B(\hat{n})$ is “the **curl**”



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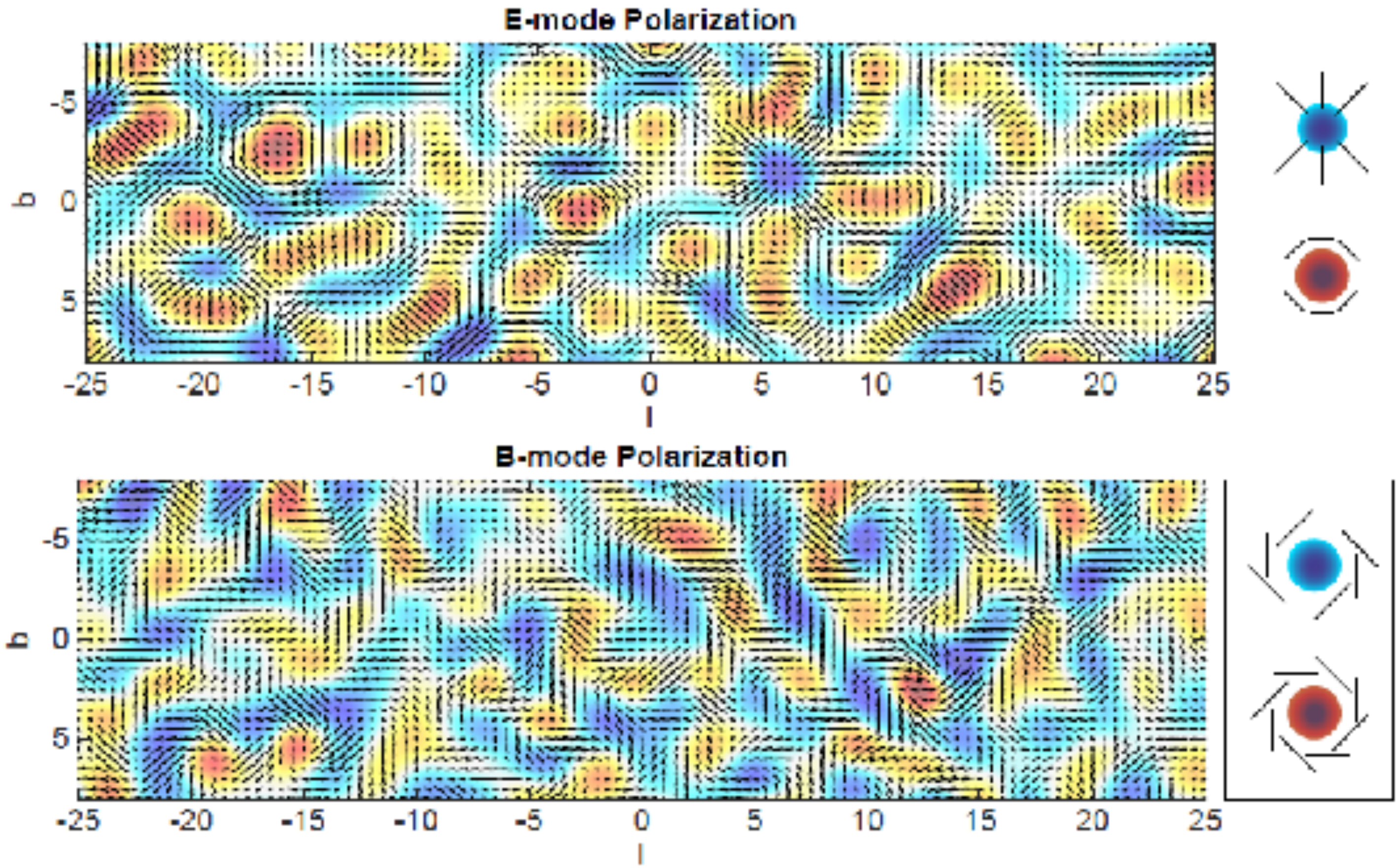

Anisotropies in CMB induce two types of polarization: gradient E- and curl B-modes

arXiv:1510.06042

Reminder: Thomson Scattering

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$$\frac{I}{I' \, \Delta\Omega} = \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{3\sigma_{\mathrm{T}}}{8\pi} |\hat{\epsilon}' \cdot \hat{\epsilon}|^2$$

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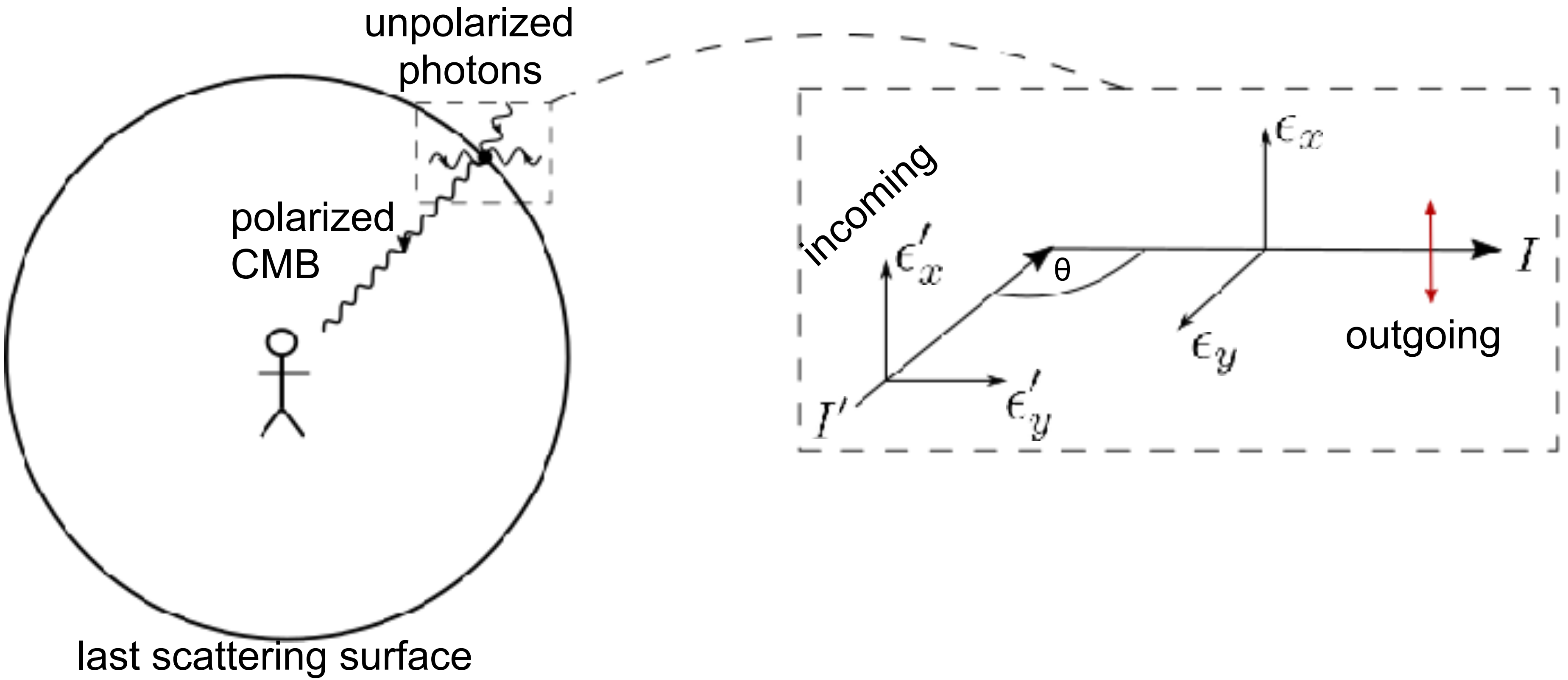

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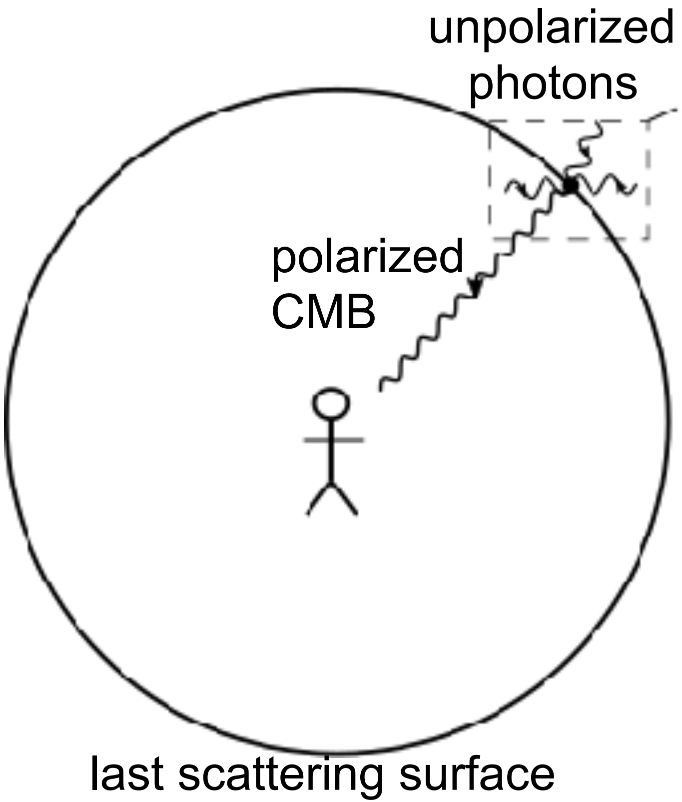

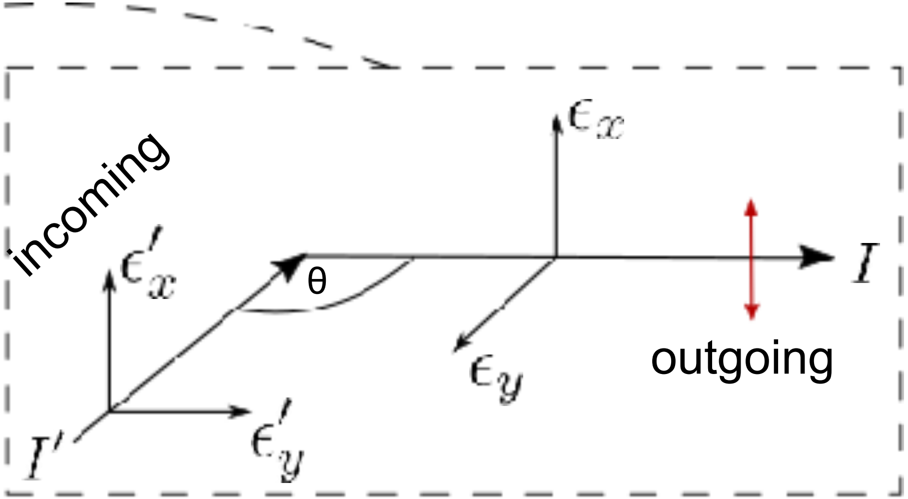

$$I_x^2 + I_y^2 = I = \frac{3\sigma_\mathrm{T}}{16\pi} I'(1 + \cos^2(\theta))\mathrm{d}\Omega$$

$$I_x^2 - I_y^2 = Q = \frac{3\sigma_\mathrm{T}}{16\pi} I' \sin^2(\theta)\mathrm{d}\Omega \neq 0$$

$$U = \ldots$$

Reminder: Thomson Scattering

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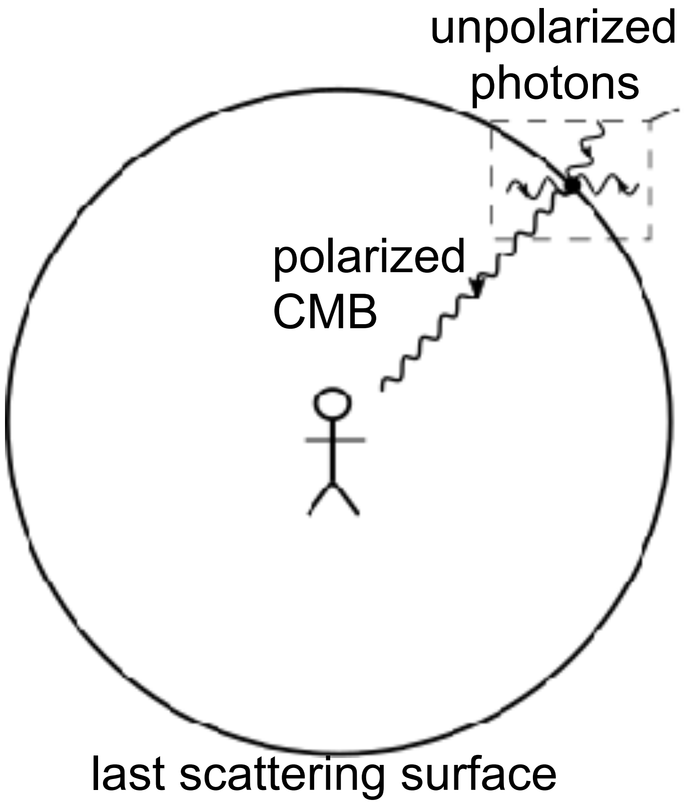

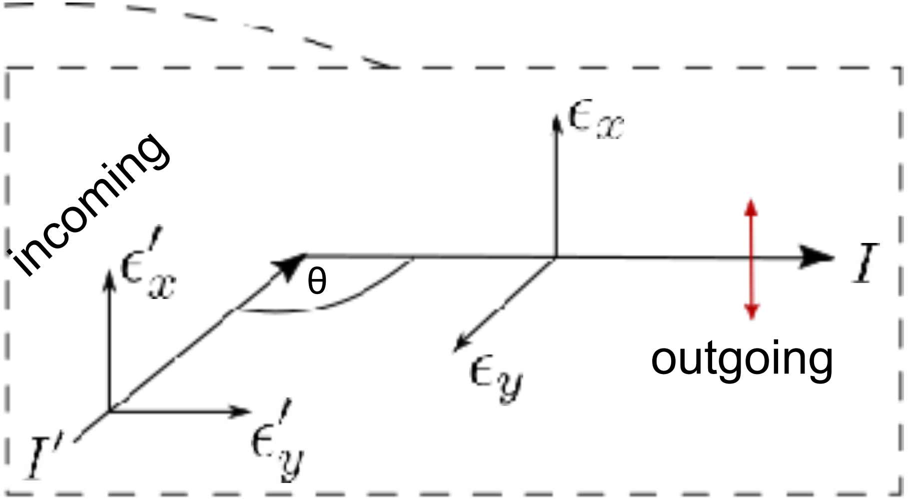

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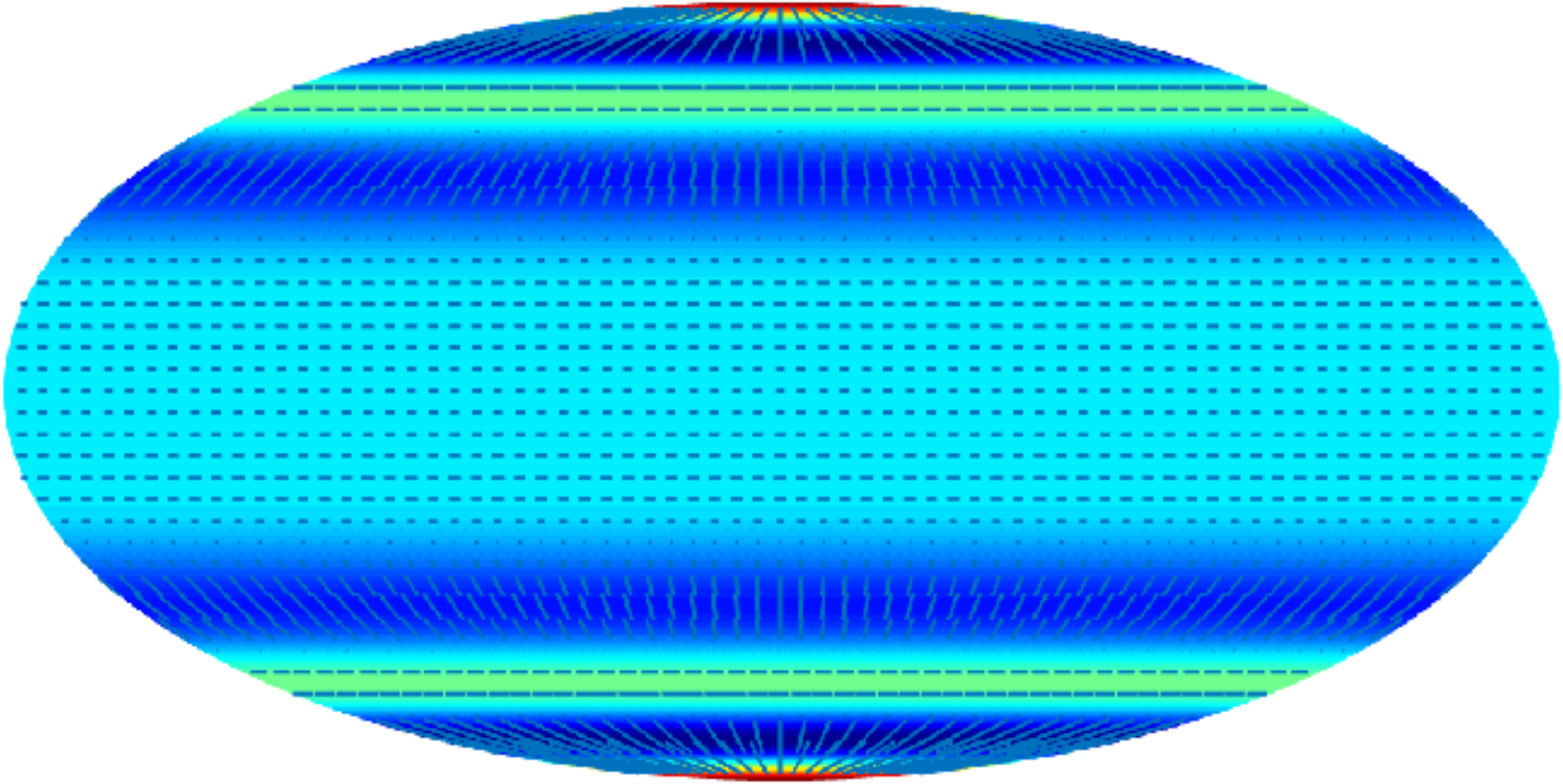
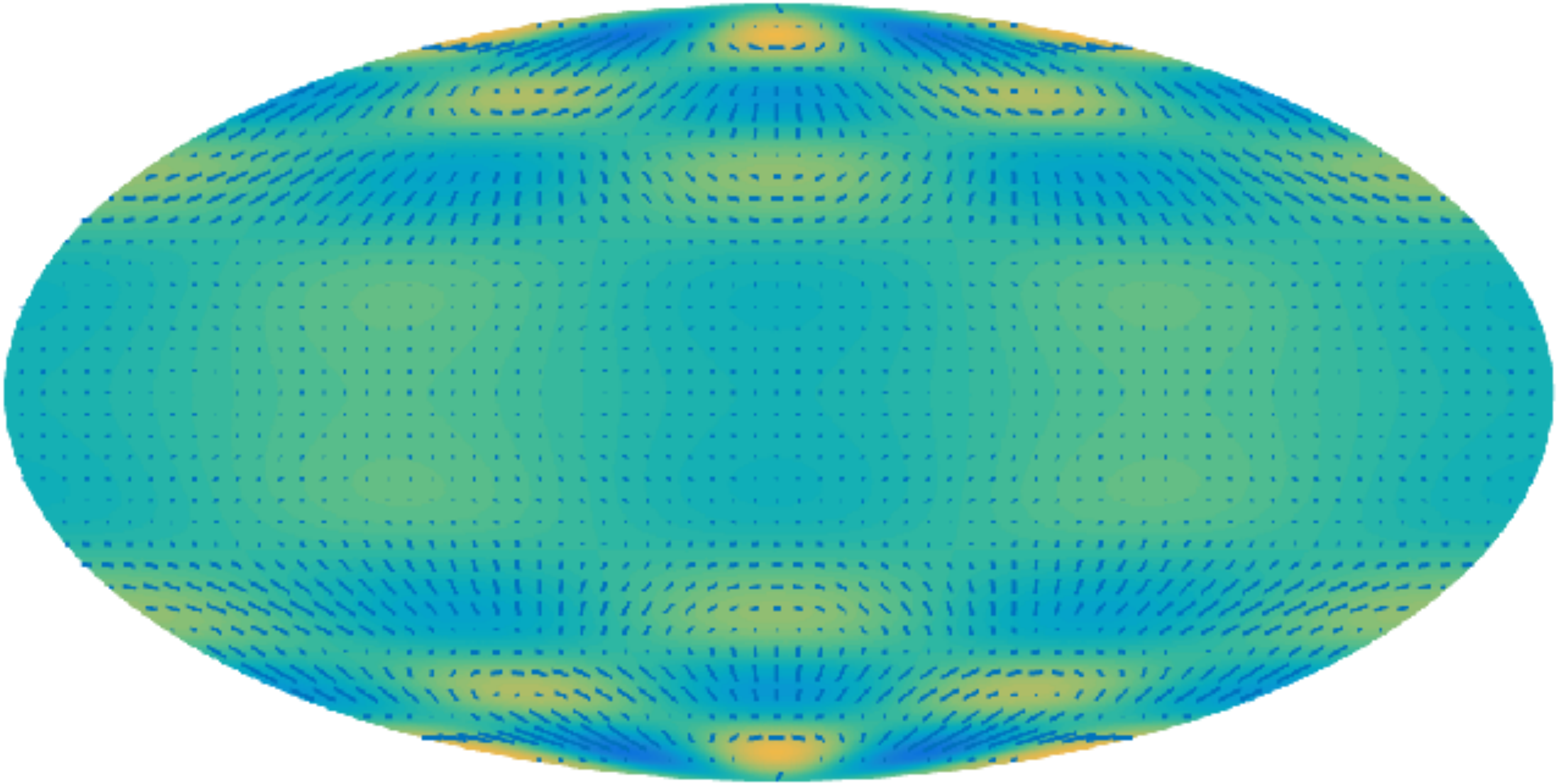


CMB with a monochromatic scalar perturbation

arXiv:1510.06042



CMB with a monochromatic GW

arXiv:1510.06042

Why are B-Modes only generated by GWs?

(qualitatively)

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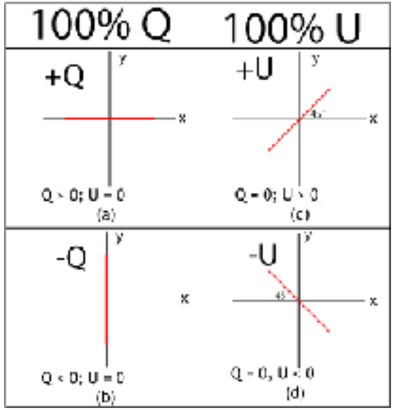
- from the picture we read off that $Q(\hat{n})$ is an even and $U(\hat{n})$ is an odd function under $\mathbb{P} = \{x \to -x\}$
- with this one checks that $E(\hat{n})$ is even and $B(\hat{n})$ **is odd**
- since scalar perturbations give rise to (even) scalar functions like $T(\hat{n})$, they cannot source $B(\hat{n})$



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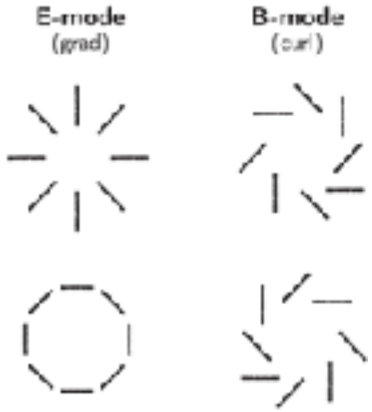

Baumann, McAllistor

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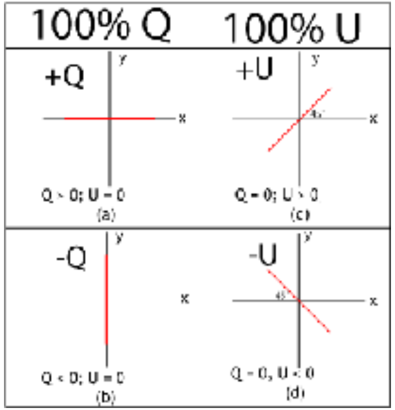
- since scalar perturbations give rise to (even) scalar functions like $T(\hat{n})$, they cannot source $B(\hat{n})$
- consider x-polarized GW:

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + \mathrm{d}x^2 + \mathrm{d}y^2 + \mathrm{d}z^2 + 2h_\times \mathrm{d}x\mathrm{d}y$$
$$\xrightarrow{\mathbb{P}} -\mathrm{d}t^2 + \mathrm{d}x^2 + \mathrm{d}y^2 + \mathrm{d}z^2 - 2h_\times \mathrm{d}x\mathrm{d}y$$

read off: amplitude $h_\times$ is odd under parity!

- **GWs are odd** and can therefore source B-modes!



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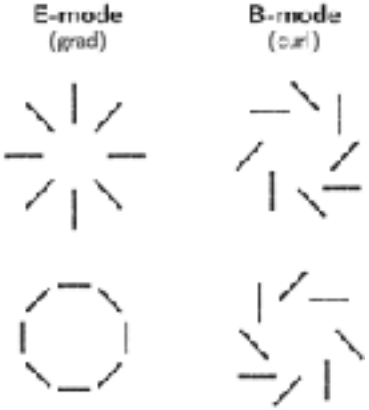

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- can be decomposed into E- and B-modes after plugging into $\mathcal{P}_{ab}$ and into **spherical harmonics** $Y_{lm}(\theta, \phi)$

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- density (scalar) quadrupole rotationally symmetric about plane wave axis $\propto Y_{20}$
  GW (tensor) quadrupole not rotationally symmetric $\propto Y_{22}$
- LHS of (1) contains E and B, RHS of (1) contains sources such as GWs;
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- **difficulty**: B-mode creation after decoupling via gravitational **lensing**

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- spectrum of GWs extracted from B-modes **test theories of primoridal GWs**, this not only includes GWs from fluctuations during inflation, but also phase transitions* (eternal inflation, EW phase transition)

- correlations larger than horizon at the time of decoupling are a test of inflation

*see Thomas' talk

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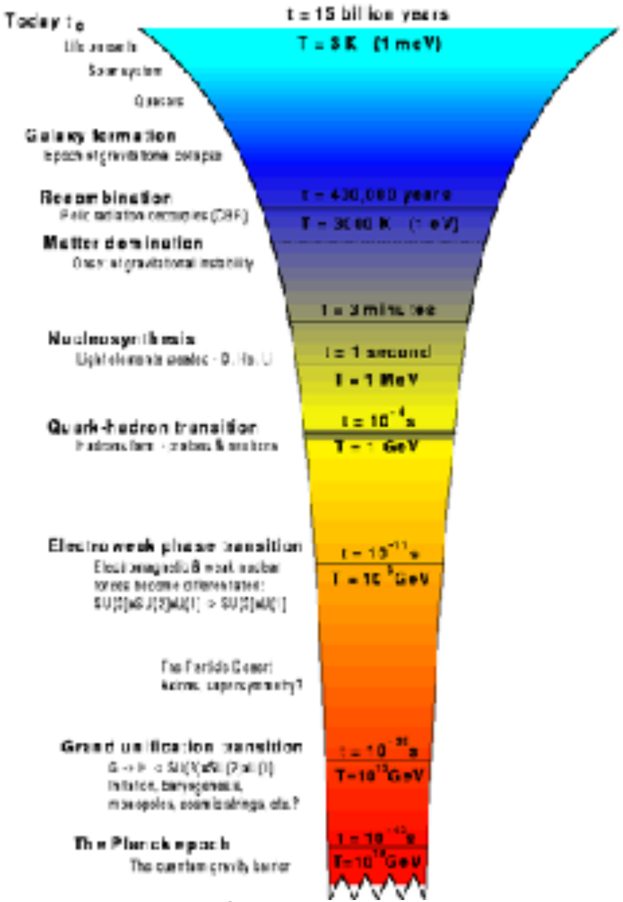
What we learn about our Universe today

- we also learn about where and how much **dust** is in the universe, see BICEP2

*see Thomas' talk

Phase transitions in the early Universe



[T.Prokopec, Lecture notes for cosmology, 2008]

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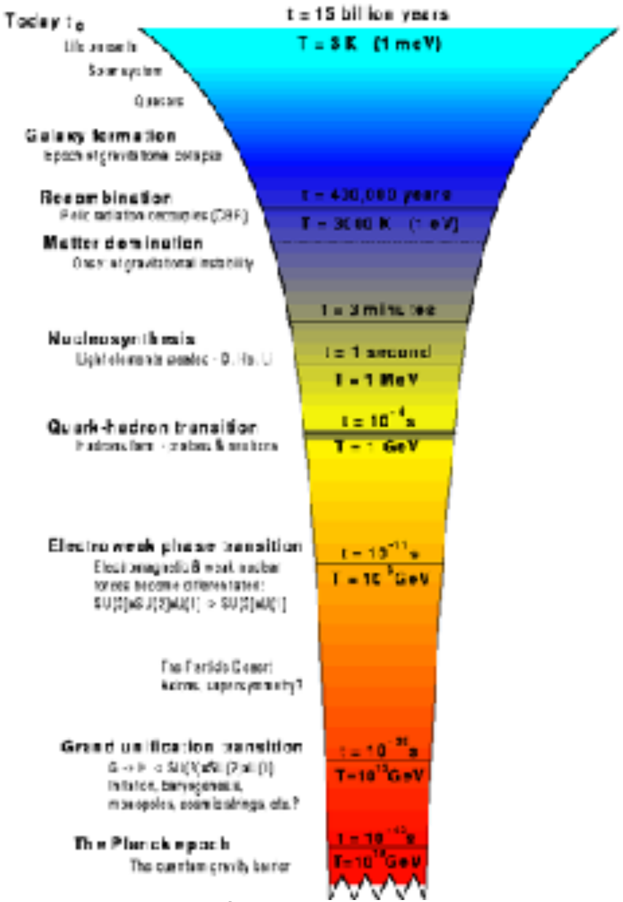

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QCD phase transition: T~O(100) MeV

- deconfinement: $'' \; SU(3)_C \times U(1)_Q \rightarrow U(1)_Q \; ''$
- chiral SB: $SU(3)_L \times SU(3)_R \rightarrow SU(3)_{L-R}$

⟶ Second order phase transition!

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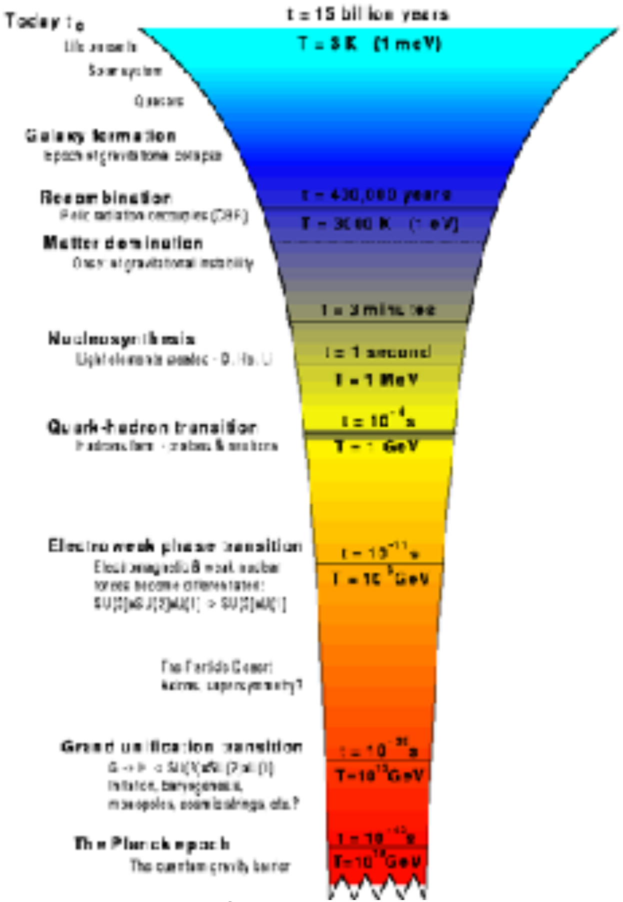

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Electroweak phase transition: T~O(100) GeV

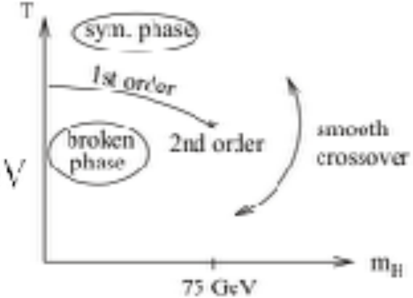
- Higgs mechanism:

$$SU(3)_C \times SU(2)_L \times U(1)_Y \rightarrow SU(3)_C \times U(1)_Q$$

- eff. scalar potential $V_{eff}(v)$

⟶ LHC:

$$m_H = 125.09 \pm 0.24 \text{ GeV}$$



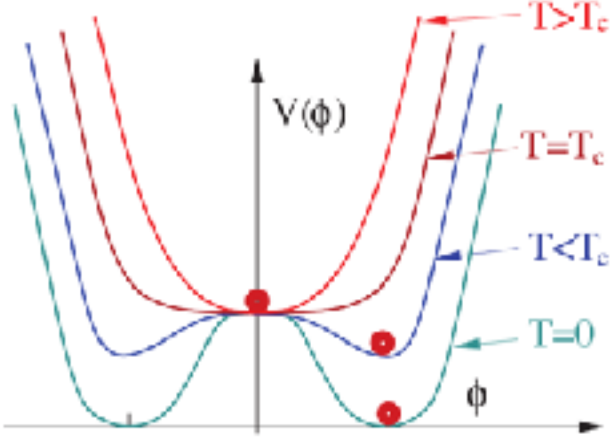
Recap: Phase transitions (PT) in toy models

Second order PT:

- real scalar field in Mexican hat

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{\lambda}{4}(\phi^2 - v^2)^2$$

- ground state (T=0): $\lambda(\phi^2 - v^2)\phi = 0$
- @ high T: symmetry restoration



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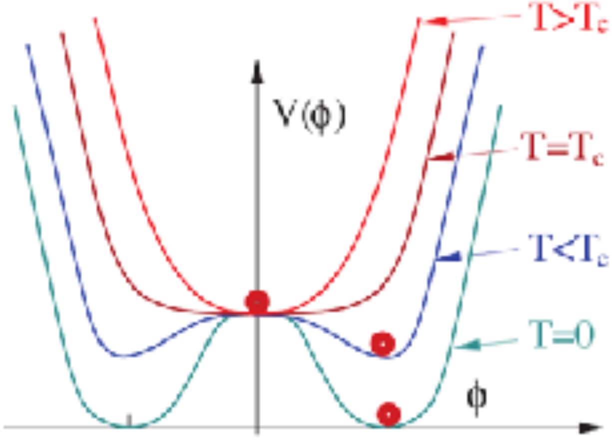
- ground state (T=0): $\lambda(\phi^2 - v^2)\phi = 0$
- @ high T: symmetry restoration
- field decomposition: $\phi(x) \to \phi_0 + \delta\phi(x)$

$$\lambda(\phi_0^2 + 3\langle\delta\phi^2\rangle - v^2)\phi_0 = 0$$

- thermal contribution: $\langle\delta\phi^2\rangle \simeq \frac{T^2}{12} + \mathcal{O}(T)$
- effective scalar potential:

$$V_{\rm eff}(\phi_0) = \lambda\left(\frac{\phi_0^4}{4} + \frac{\phi_0^2}{2}\left(\frac{T^2}{4} - v^2\right)\right)$$



[T.Prokopec, Lecture notes for cosmology, 2008]

Recap: Phase transitions (PT) in toy models

Second order PT:

- real scalar field in Mexican hat

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{\lambda}{4}(\phi^2 - v^2)^2$$

- ground state (T=0): $\lambda(\phi^2 - v^2)\phi = 0$
- @ high T: symmetry restoration

- field decomposition: $\phi(x) \to \phi_0 + \delta\phi(x)$

$$\lambda(\phi_0^2 + 3\langle\delta\phi^2\rangle - v^2)\phi_0 = 0$$

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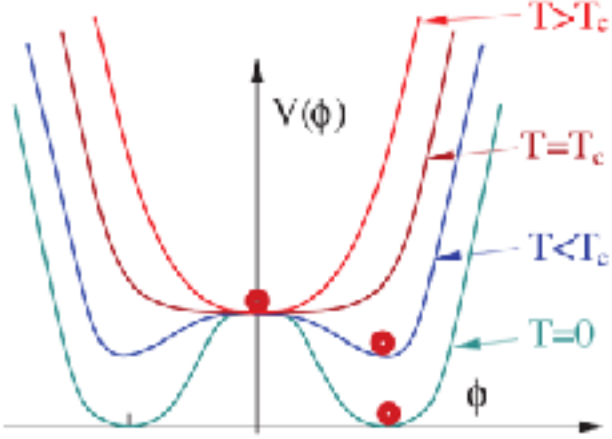


[T.Prokopec, Lecture notes for cosmology, 2008]

- continuous in the order parameter
- thermal equilibrium
- no bubbles for T<T_c

Recap: Phase transitions (PT) in toy models

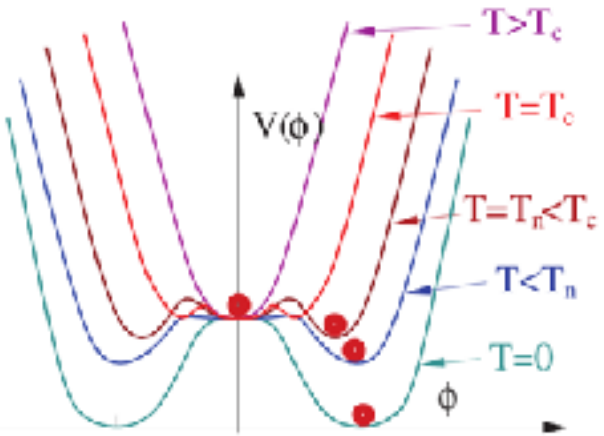
First order PT:

- scalar QED:

$$\mathcal{L} = D_\mu \phi^* D^\mu \phi - \frac{\lambda}{4}(\phi^* \phi - v^2)^2 - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

- field decomposition(wlog):

$$\phi_1 = \phi_0 + \delta\phi_1$$
$$\phi_2 = \delta\phi_2$$



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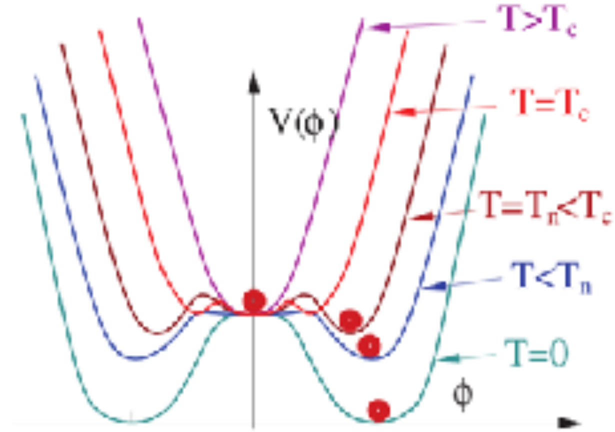
- effective potential:

$$V_{\rm eff}(\phi_0) = \frac{1}{2}\left[\left(\frac{\lambda}{3} + \frac{g^2}{4}T^2 - \lambda v^2\right)\right]\phi_0^2 - \frac{g^3 T}{4\pi}\phi_0^3 + \frac{\lambda}{4}\phi_0^4$$



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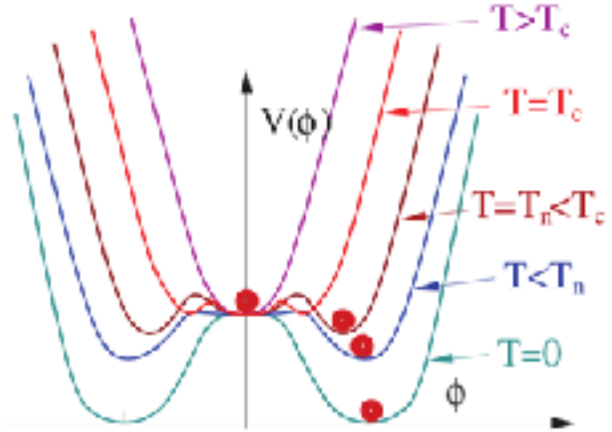

[T.Prokopec, Lecture notes for cosmology, 2008]

- $T<T_c$: maxima develop → barriers
- $T<T_n$: barriers become smaller, tunnelling probability increases
- bubble formation in background of false vacuum

Generic picture: GW from cosmological first order PT

1. bubble nucleation into low-T phase

   tunnelling or thermal fluctuations

1. bubble expansion & bubble collision:

   latent heat rises T_{Plasma} & E_{Kin} of bubble wall and bulk

[D.J.Weir, Phil.Trans.Roy.Soc.Lond. A376, 2018]

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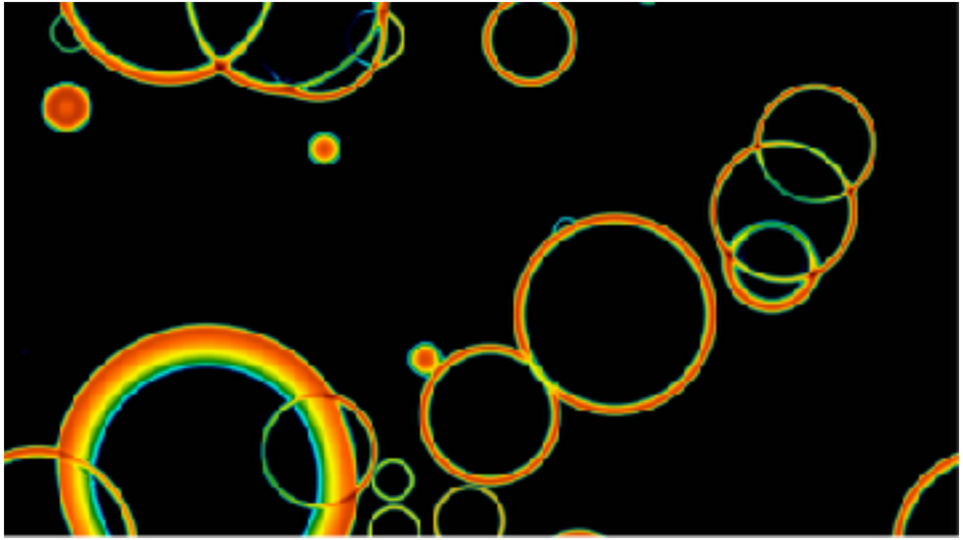

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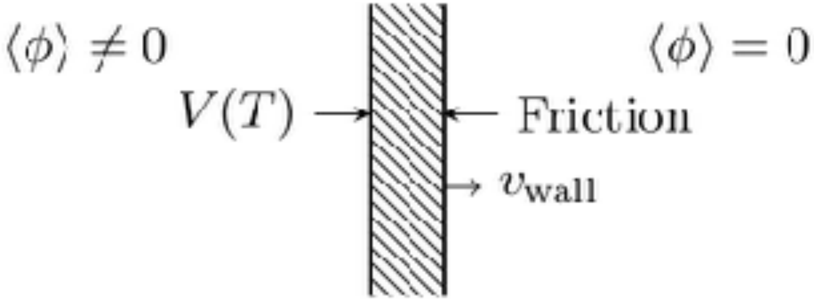

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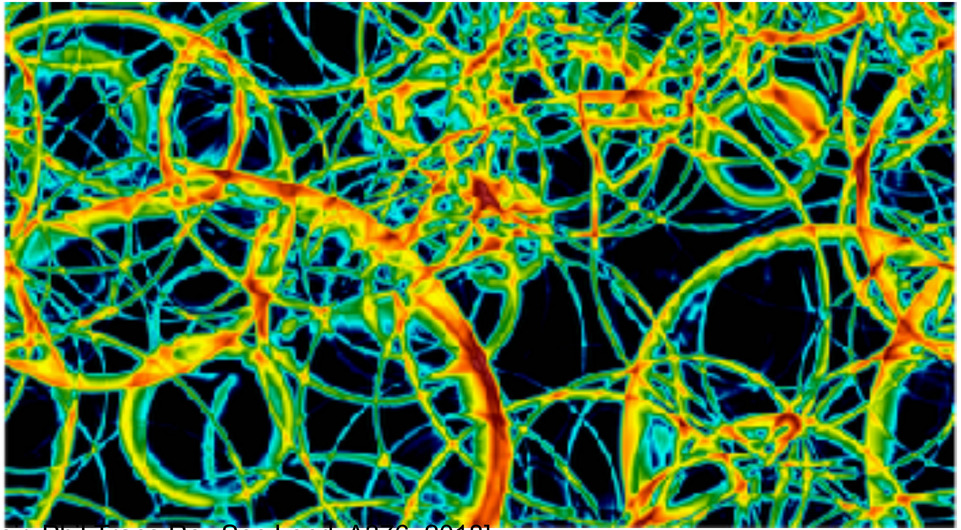

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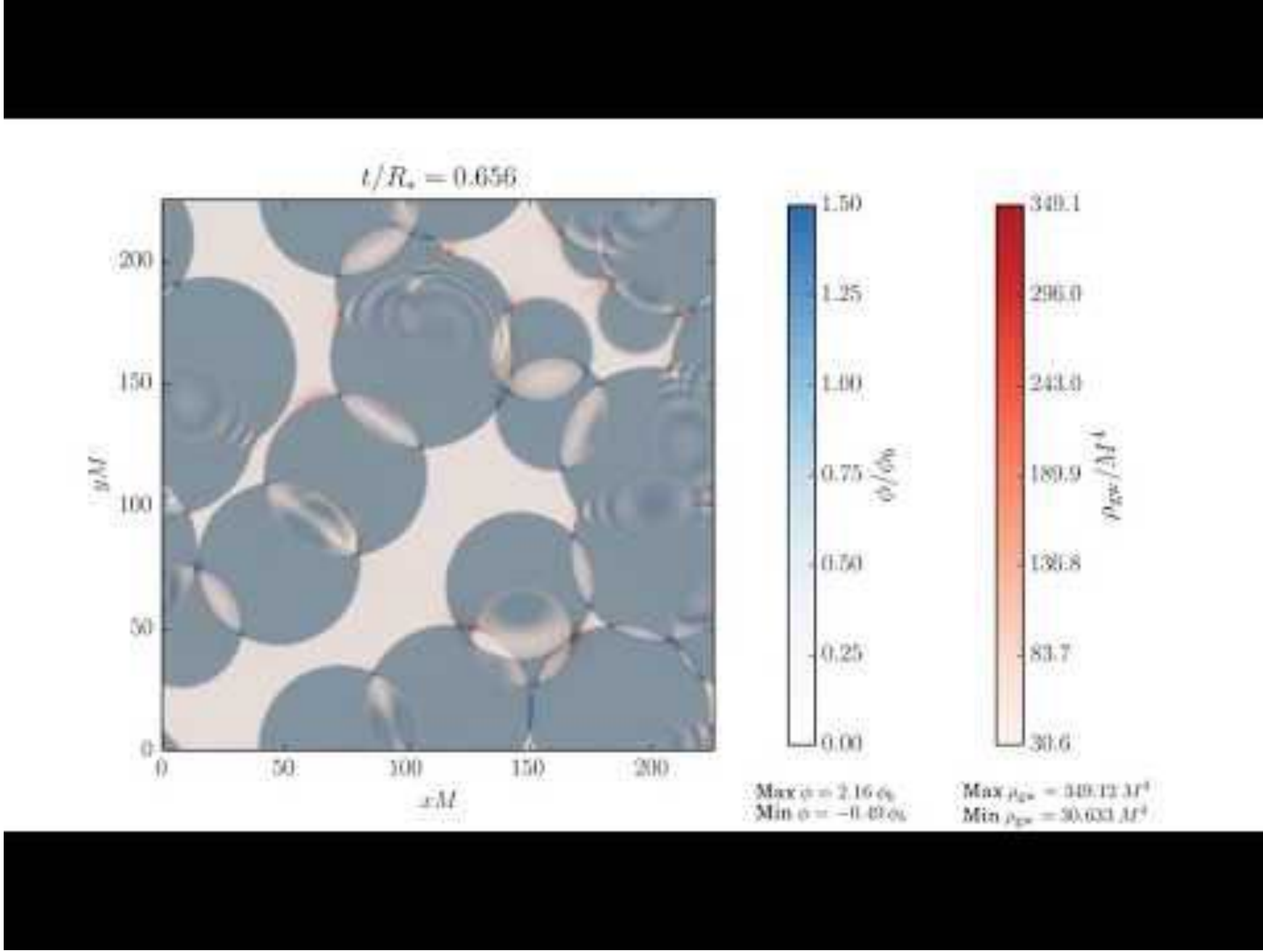
Bubble formation & collision



Youtube: https://www.youtube.com/watch?v=Ggs2fQL0ICU0

Bubble collision and origin of gravitational waves

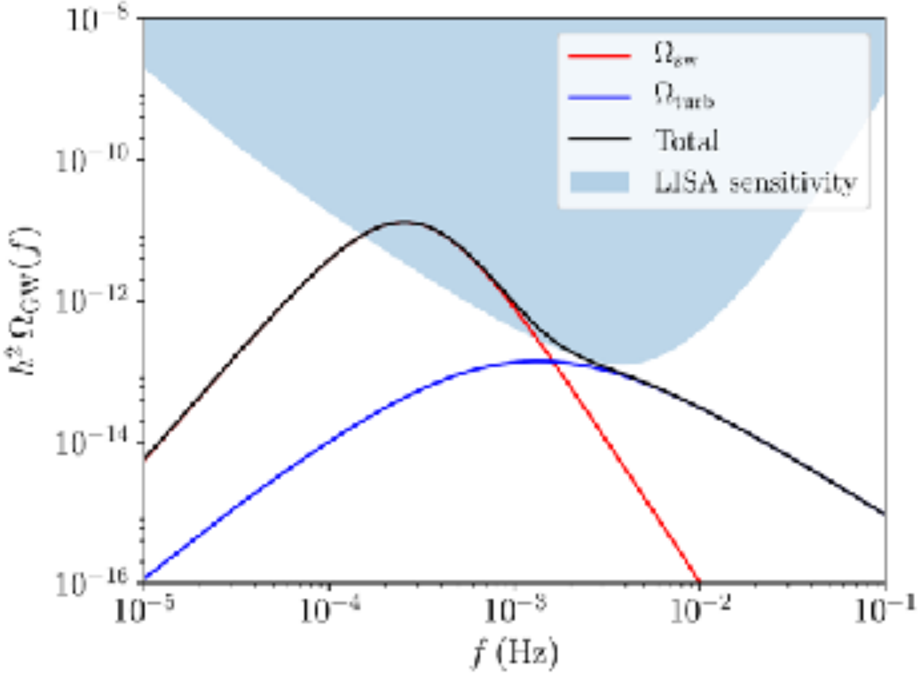
GW production through 1OPT can be devided into three stages:

$$\Omega_{GW} = \Omega_{env} + \Omega_{sw} + \Omega_{turb}$$

1. initial collision of scalar field shells (generally subdominant)

1. wave of kinetic energy within plasma

1. shocks & turbulence (typical time- and length-scales?)



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$$h^2\Omega_{env}(f) \simeq 1.65\cdot 10^{-5}\,\Delta(v_w)\left(\frac{H_*}{\beta}\right)\left(\frac{\kappa_\phi\,\alpha_{T_*}}{1+\alpha_{T_*}}\right)^2 S_{env}\left(\frac{f}{f_{env}}\right)$$

$$f_{env} \simeq 16.5\ \mu\text{Hz}\ \left(\frac{f_*}{\beta}(v_w)\right)\left(\frac{\beta}{H_*}\right)$$

1. wave of kinetic energy within plasma

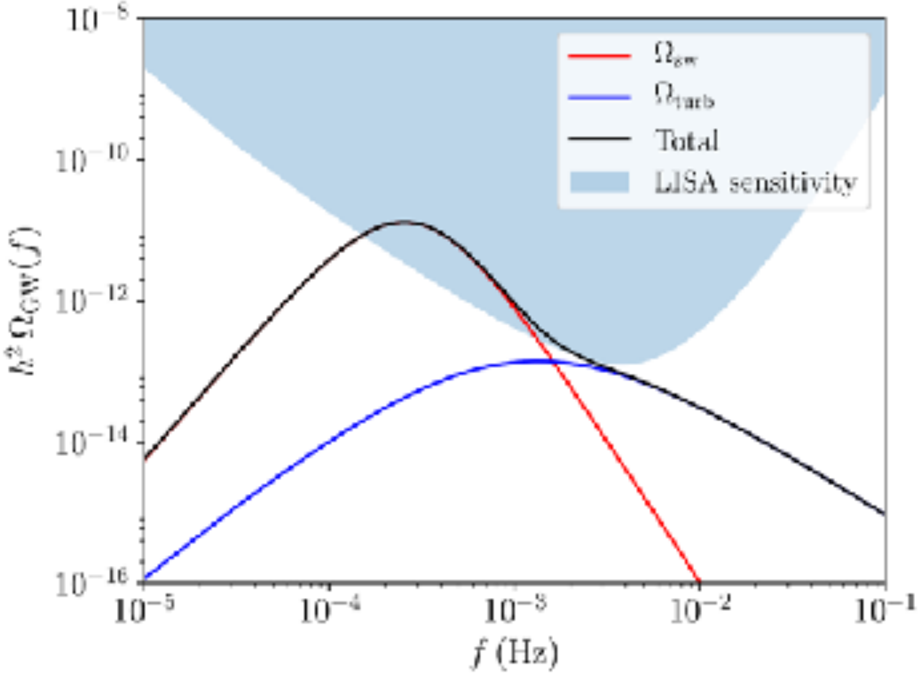
$$h^2\Omega_{sw}(f) \simeq 8.5\cdot 10^{-6}\ \overline{U}_f(\kappa_f,\alpha_{T_*})^4\left(\frac{H_*}{\beta}\right) v_w S_{sw}\left(\frac{f}{f_{sw}}\right)$$

$$f_{sw} \simeq 8.9\ \mu\text{Hz}\ \left(\frac{1}{v_w}\right)\left(\frac{\beta}{H_*}\right)$$

1. shocks & turbulence (typical time- and length-scales?)

$$h^2\Omega_{turb}(f) \sim 3.35\cdot 10^{-4}\ \left(\frac{H_*}{\beta}\right)\left(\frac{\kappa_{turb}\,\alpha_{T_*}}{1+\alpha_{T_*}}\right)^{\frac{3}{2}} v_w S_{turb}\left(\frac{f}{f_{turb}}\right)$$

$$f_{turb} \simeq 27\ \mu\text{Hz}\ \left(\frac{1}{v_w}\right)\left(\frac{\beta}{H_*}\right)$$



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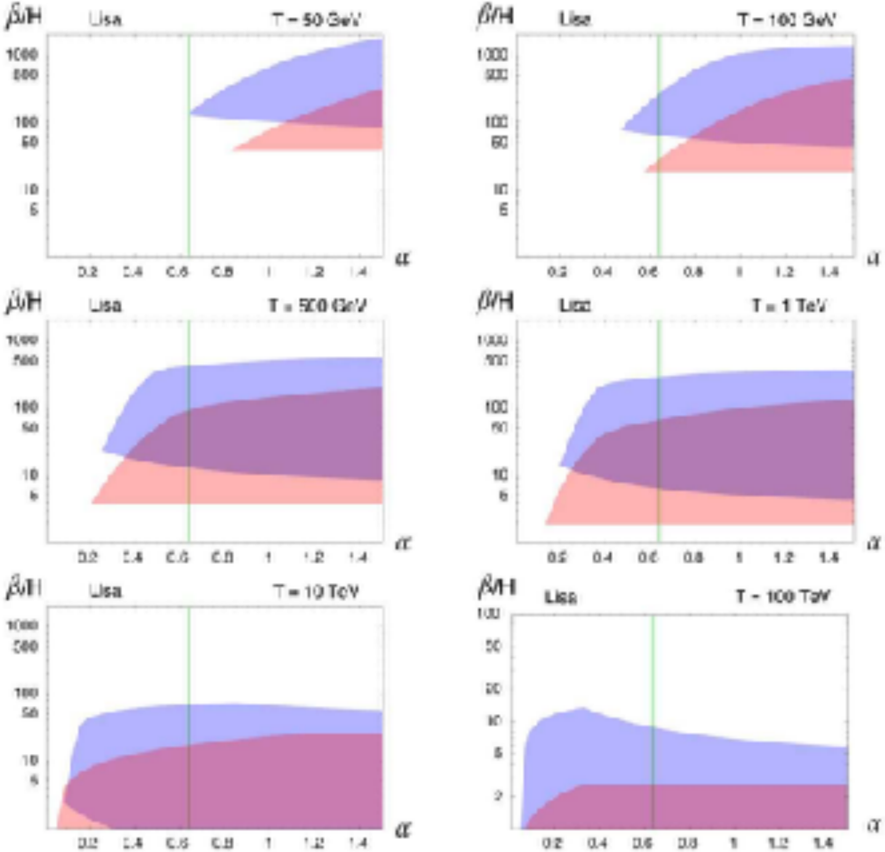
Key parameter of GW spectrum



[C.Grojean & G.Servant, Phys.Rev. D75, 2007]

Key parameter of GW spectrum

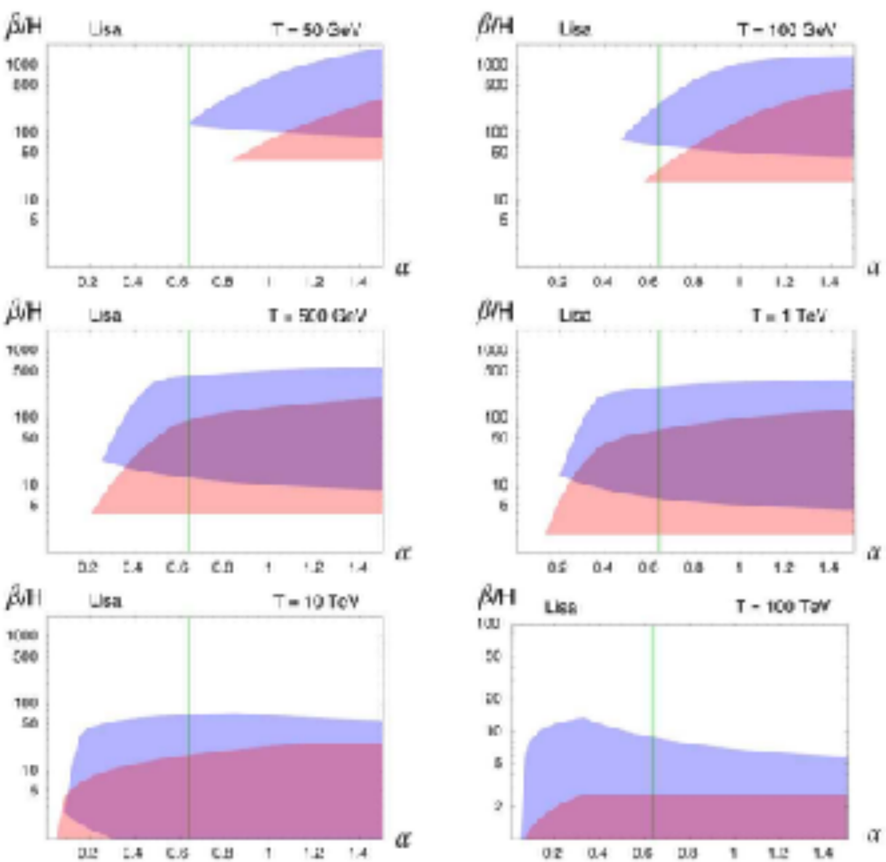
1) Change of bubble nucleation rate: $\frac{\beta}{H_*} = T_* \frac{d}{dT}\left(\frac{S_3}{T}\right)\Big|_{T_*}$

- free energy of critical bubble:

$$S_3 = 4\pi \int r^2 dr \left(\frac{1}{2} \left(\frac{d\phi_b}{dr} \right)^2 + V(\phi_b, T) \right)$$

- bounce solution:

$$\frac{d^2\phi_b}{dr^2} + \frac{2}{r}\frac{d\phi_b}{dr} - \frac{\partial V}{\partial \phi_b} = 0 \quad \text{with} \quad \frac{d\phi_b}{dr}\Big|_{r=0} = 0, \;\; \phi_b|_{r=\infty} = 0$$



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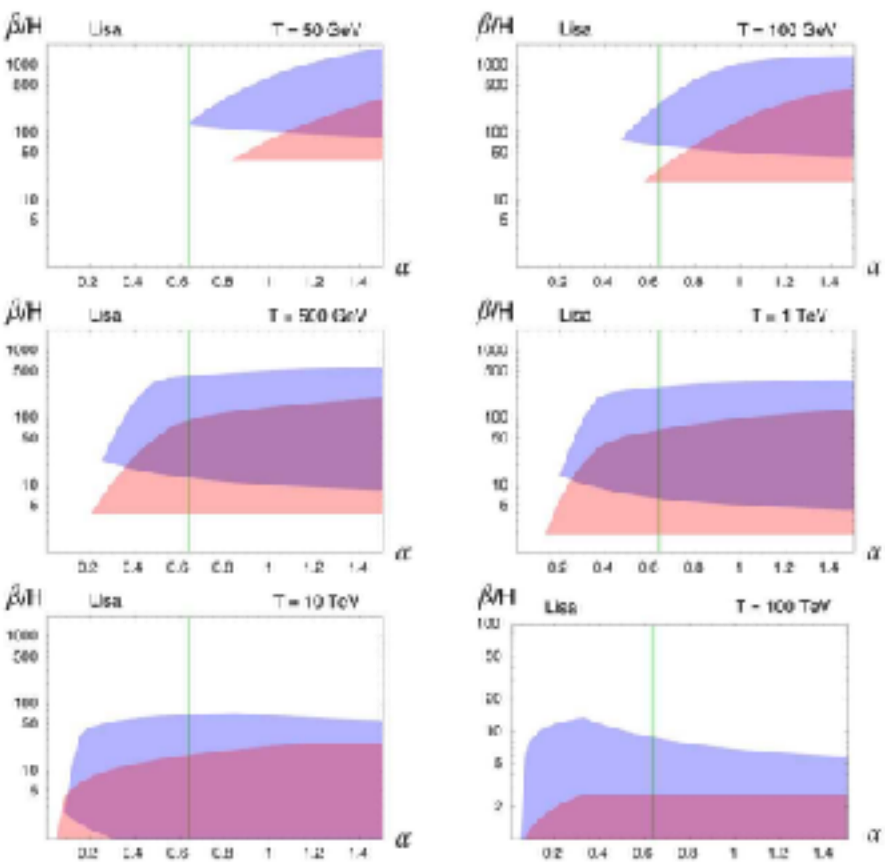
2) Latent heat to energy density ratio $\alpha = \frac{\epsilon}{\rho_{\rm rad}}$

- two contributions to latent heat:

$$\epsilon = -\Delta V - T\Delta s = \left(-\Delta V + T\frac{\partial V}{\partial T}\right)_{T_*}$$



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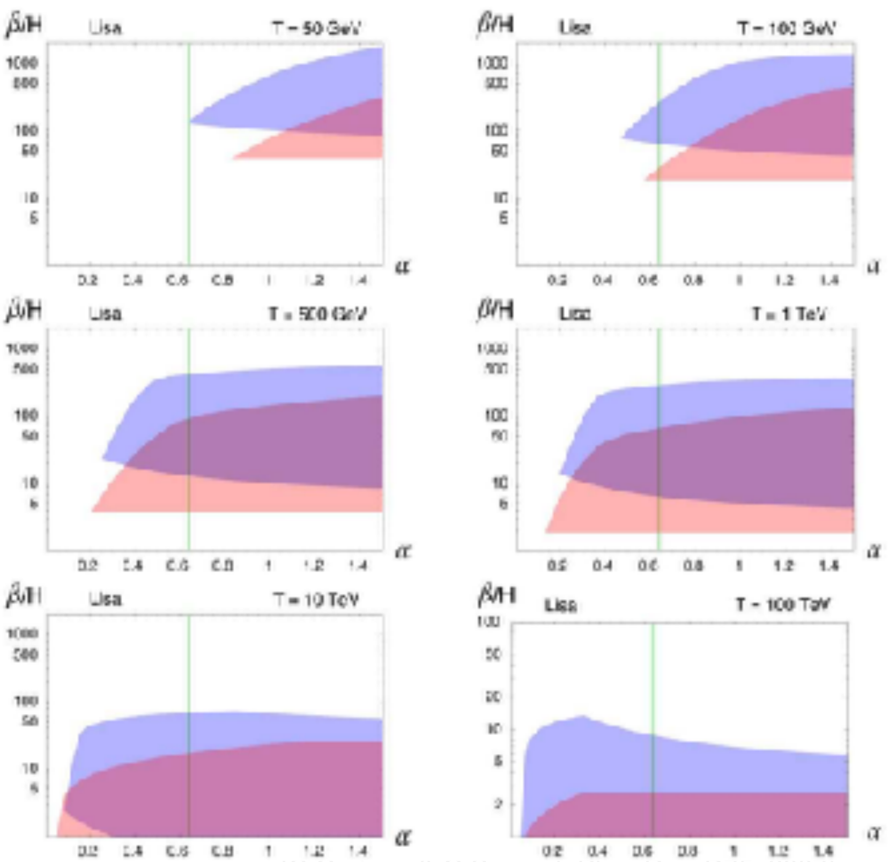
GW are **insensitive** to:

- internal bubble structure
- small scale field configuration in the collision region



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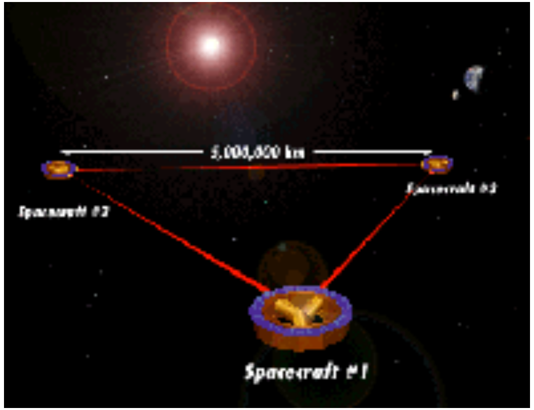
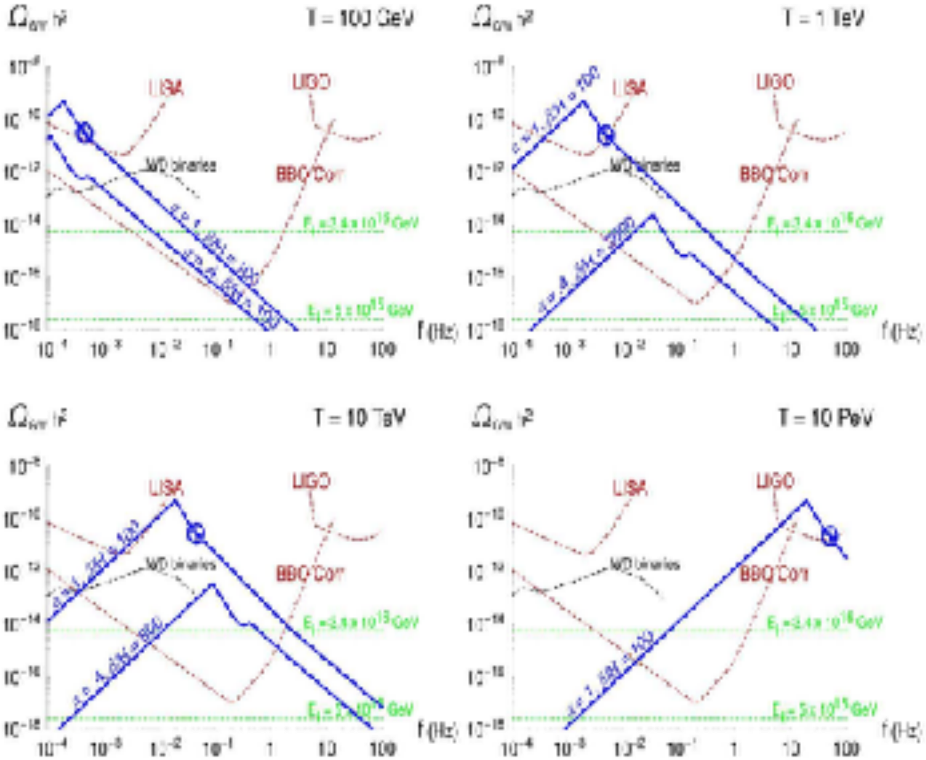
Detection possibilities of future experiments

- LISA sensitive to 10 TeV
- LIGOIII, LISA & BBO will probe T~100-10^7 GeV
- GW from PTs around 10-100 TeV could entirely screen signals from inflation!



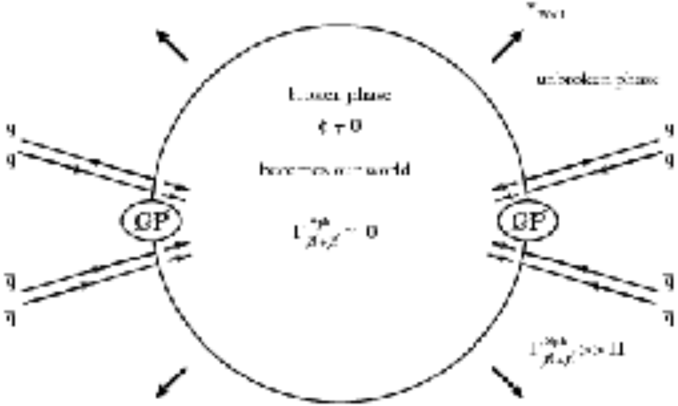


[http://web.mit.edu/klmitch/classes/8.224/project/lisa.html]

[C.Grojean & G.Servant, Phys.Rev. D75, 2007]

Phase transitions & BSM physics

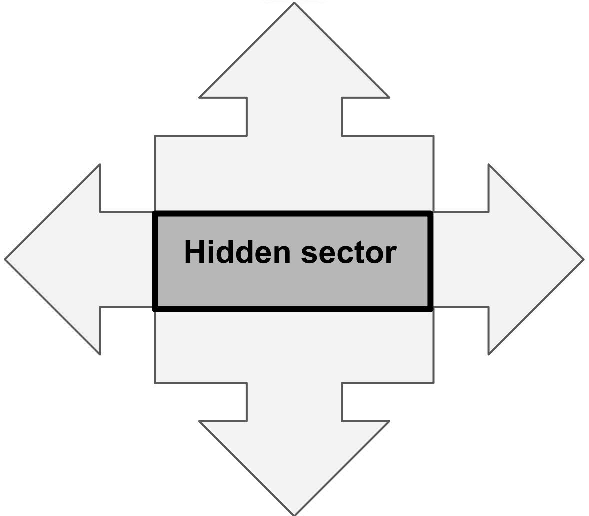
[W.Buchmüller, Acta Phys.Polon. B43, 2012)]



Search: GW from first order PT

1. Modification of electroweak PT
    - electroweak baryogenesis
    - Higgs portals

1. First order PT in new (yet hidden) sectors
    - new scalars
    - new forces & symmetry breaking



Conclusion:

- If inflation took place, GWs produced during that time, would actually survive untill CMB and can be even observed.
- Primordial GWs would be a model-independent evidence of the concept of inflation.
- GWs leave a unique imprint on the CMB in the form of polarization
- The extracted spectrum can give hints to their origins (e.g. low frequencies for inflationary GWs)
- GW from particle physics PT directly related to associated scalar potential
- “new”/old tool for future particle phenomenology!

Thank you!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